HARRAP'S TORCH BOOKS
GENERAL EDITOR: C. L. BOLTZ

HOW RADAR WORKS

BY

KENNETH ULLYETT
F.R.Met.S. A.M.S.E.

With Five Plates in Half-tone and Line Drawings and Diagrams in the Text

GEORGE G. HARRAP & CO. LTD
LONDON SYDNEY TORONTO BOMBAY

First published 1948
by GEORGE G. HARRAP & CO. LTD
182 High Holborn, London, W.C.1

THIS BOOK IS PRODUCED IN
COMPLETE CONFORMITY WITH THE
AUTHORIZED ECONOMY STANDARDS

Composed in Plantin type and printed by Western Printing Services, Ltd,

EDITOR'S FOREWORD

"HARRAP'S TORCH BOOKS" ARE INTENDED TO SERVE A wide public with accurate, up-to-date science interestingly arranged and illustrated, each book written by an author experienced in explanation and well qualified in his subject.

Having regard for the reader's comfort and convenience, the authors have made the treatment popular; having an equal regard for his intelligence, they have included the fundamentals, without which any knowledge of a subject is worthless. Every reader can be sure that he will find in these books what is true, what is useful, and what is provocative of thought.

"Knowledge is power," wrote Bacon; moreover, it is the only power that does not carry in itself the seeds of its own corruption; there is no substitute. Knowledge, indeed, is the only power worth pursuing in this modern world. And in the pursuit we shall gain understanding and stay humble if we remember our heritage, the work of all those who have gone before to guide us. To this end the authors of this series make use of the historical approach.

A *torch* lights the way in the dark and assists us through fog; it has for centuries been a symbol of learning; as a traffic sign it warns us that we are coming to a school. And, just as important, a torch spreads its light on every one within its ambit, making no distinction between rich and poor or young and old.

C.L.B.

PREFACE

SINCE THE EVOLUTION CONTROVERSY AT THE CLOSE OF the nineteenth century the scientific method of objective observation, experiment, and cool statistical examination has invaded every department of knowledge, almost, it would seem, to the total exclusion of genius. This book is, however, an introduction to a branch of electronics (which is itself a new department of the general subject of physics) known as radar; and radar is a development of well-known electrical and radio principles in a sequence of discoveries in which the physicists involved in such development have not been reluctant to admit the entry of genius to their work.

As one of those onlookers permitted for a number of years to study the sequence of inspired stages of development by Sir Robert Watson-Watt and his colleagues, I should like this book to be a humble tribute to their work. The reading of it demands no specialized knowledge of physics, but an assumption is made that the reader knows the most elementary mathematics, and is familiar with the functioning of conventional broadcast-reception equipment up to the application of superheterodyne action. As an explanation of the basic principles of popular types of radar equipment the book is in no sense a work of reference, and for this reason sources are not quoted at length. However, in the preparation of this work I have had the most generous co-operation from the Services and Supply Ministries concerned with radar's production and operational use, and from the research laboratories of the British and American radio and radar industries.

In particular I wish to record my thanks to the former Ministry of Aircraft Production for the loan of documents. Thanks are also due to the Admiralty Signal Establishment, to the Air Ministry, to Sir Robert Watson-Watt, to Dr R. A. Smith for notes on radar navigation systems, to Dr L. Huxley for information on basic radar principles, to the Publication Board of the Radio Research Laboratory at Harvard University, and to the directors of the research laboratories of A. C. Cossor, Ltd, and the General Electric Co., Ltd.

K. U.

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I. THE DISCOVERY OF RADAR

It would have been comparatively simple, a few years ago, to define radar as a means of ascertaining location by radio echo. Indeed, the essence of Sir Robert Watson-Watt's discovery seemed at first to be that radar, distinct from any other form of position-finding, needed no co-operation on the part of the target. A chain of coastal, and subsequently, inland warning radar stations was erected the major purpose of which was to detect and locate a target without the target being made aware of the invisible radar beam tracking it through clouds and in dark of night.

To-day radar is not confined to systems where the echo from a radio pulse of energy is used. So complex has the wide field of radar and kindred radio navigational aids become that we must include Oboe, Gee, Rebecca-Eureka, and other famous systems. In these it is not merely a matter of broadcasting a pulse and detecting the echo: some complex systems include transmitters which are 'triggered off' by the incoming pulse, and themselves retransmit a spurt of radio energy which a suitably placed receiver picks up. Radar is used for timing, plotting, course-checking, and, indeed, for many major navigational tasks where the echo of a series of pulses is not by any means the major feature of the operation. There is, in fact, no greater similarity between the early echo systems of radar (which protected the shores of the British Isles at the beginning of the Second World War) and the latest radar navigational aids than there is between a carborundum-crystal receiver and a modern television receiver. They have

radio communication as a common link, and that is about all.

This invention, with its limitless applications in the air and at sea, was born simultaneously with the accession to power of the Nazi party in Germany. Had British scientists not been working upon this invention long before Europe burst afresh into the flame of war it is very doubtful indeed whether we in these islands would have been able to hold out in the critical times of our lonely struggle in 1940–41. From those grim war years radar has risen from the obscurity of an untested scientific trick of unknown operational value to a peace-time system in which radio is used in a diversity of ways as a navigational aid.

Countless generations before the first radar system was devised by man Nature had given us a perfect example of a workable radar navigational aid in the mechanism which enables bats to fly. Recent research, in the light of our present knowledge, shows that the bat is provided with a mechanism which is a strange parallel of radar.

In the first-devised radar systems a pulse of radio energy is transmitted at a very high frequency many times a second; as each pulse strikes an object there is a reflection, received during the silent period before the next pulse is transmitted. Thus not only is an indication given of an object capable of reflecting radio waves, but if the time interval be recorded for the pulse to travel from the transmitter to the object and back—at the constant speed of light, 186,240 miles per second—then the distance of that object can be known. These pulses are transmitted at a very high frequency, so there is little chance of interference with other radio signals on more normal frequencies, and several such transmissions can be made simultaneously.

Nature for July 13, 1946, gave a detailed account of scientific research into the peculiar mechanism which enables the bat to transmit two high-pitched supersonic notes simultaneously. One is a note of a frequency of somewhere around 7000 cycles a second. This is on the upper limit of the average human ear's detection, though some people with auditory systems capable of appreciating very high frequencies can detect the shrill, continuous sound. At the same time the bat emits another sound, at a much higher frequency, so high, in fact, that to the human ear it cannot be detected as a sound. To use this high frequency for its 'radar' the bat has a special construction of nose, throat, and ear; careful study of these parts of a bat show that they are thus designed even more intricately than any human physicist could fashion a supersonic radar apparatus.

Many existing radar devices are arranged so that the outgoing, powerful signal does not register; only the returning response does so. The transmitted pulse is suppressed at the receiver. You might think that it would be quite impossible for Nature to arrange a similar device in the structure of the bat, but close examination shows us that there is a muscle in the auditory system which appears to make the bat deaf at the minute instant of the emission of the high-frequency note, so that it can hear only the echo coming back from objects it might otherwise hit in its flight. Films taken by infra-red light at night show that the bat's radar system is so sensitive that it can detect an echo-response from a tiny insect flying past.

So close are we to world-shattering events and discoveries that it is difficult for us to know if radar was merely a development and a logical step forward in science. All the fighting services paid glowing tribute to the help radar gives in war. Now that we face greater

and more beneficial applications of radar to peacetime needs it is somewhat invidious to attempt an investigation into the question of who invented it. No one individual, group, or nation can rightly claim to have invented such a complex system, any more than one single inventor can be named for the locomotive, the automobile engine, or the aircraft. It is certainly true, however, that the bulk of all radar development has been achieved by British scientists, and under the stern necessity of war Britain produced the first workable radar system, and at all important times has kept far ahead in research. Sir Robert Watson-Watt pioneered and developed radar, and it is possible to draw a parallel between his magnificent work in this branch of radar physics and the pioneer work of the Stephensons, father and son, in the development of the locomotive. If the name of Watson-Watt should rank equal with that of Edison, Alexander Graham Bell, or of other pioneers it is partly because radar now at this moment in the world's history holds a potentiality at least as great as that facing these earlier men of science.

Before taking up the threads of the recent story of radar it is interesting to look back to the year 1926, when British Patent No. 292,285, applied for by John Baird, described an arrangement which now bears a striking resemblance to H2S,[1] which we now know to be one of the most advanced radar techniques. In this patent Baird stated that radio waves can be reflected and refracted like visible light waves, and contemplated "a method for viewing an object, consisting in projecting upon it electromagnetic waves of short wavelength." In this proposed system reflections of radio waves from an object were to be passed through a 'scanner' to a receiver, and the output of this receiver was to be used for modu-

[1] See Chapter X for a detailed description.

lating a source of visible light. This link in the chain was, to a certain degree, wishful thinking in the year 1926, as there was then no known way of modulating the light with the requisite degree of speed and precision. But the patent boldly stated that a spot of light projected from this source would "traverse a screen in synchronism with the exploration of the object." Although it is very doubtful if such a system could be made to work (the 'scanning' was to be done on the receiving side, and not by the exploration of the object with the transmitted radio-wave beam, as in modern H2S), this British patent is nevertheless a step in radar development.

French technicians were also early in the field of radar, and in 1933 were working on a system of 'obstacle detectors,' using what was at that time thought to be the fantastically short wavelength of 10 centimetres. A bowl-shaped reflector as part of a radio obstacle detector was fitted near the bridge of the *Normandie* in 1935, and a year later a decimetre radio set was installed by the S.F.R. at the entrance to the port of Le Havre, at Saint-Adresse. A 10-centimetre radio link was also used across the Channel in 1934, the British organization of Standard Telephones and Cables being concerned with these tests, and a number of phenomena, now easily explained in the light of our present radar knowledge, were observed.

America too was making headway, and as early as the autumn of 1922 Dr Hoyt Taylor and Leo C. Young noticed a distortion, or 'phase-shift,' in the received signals due to reflection from a small steamer on the Potomac. To-day we should consider their results remarkable, because the steamer had a wooden hull and there was very little metal or conducting material in the construction to accentuate such a phase-shift. The

wonder is that the U.S. Navy Department, for whom Taylor and Young were working then as civilian scientists, did not make more immediate use of their important discovery. It was not until the summer of 1930 that the same men, experimenting with radio direction-finding equipment, made the second important observation that reflections of radio waves from an aircraft could similarly be detected. The phase-shift of the radio waves was observed, but no practical means of display was found.

The principle of pulse-ranging, which characterizes modern radar, was used first in Britain, but the earliest public announcement was made in the United States in 1925, when Dr Gregory Breit and Dr Merle Tuve, of the Carnegie Institution of Washington, used a beam of radio energy to measure the distance from the earth's surface to the ionosphere, the radio-wave-reflecting layer near the outer skin of the earth's atmosphere. The technique consists of sending skyward a train of very short radio pulses, a minute fraction of a second in length, and measuring the time taken for each reflected pulse to return to earth.

In Britain Dr E. V. Appleton and the Department of Scientific and Industrial Research had been working along parallel lines. Appleton had trained a number of ionosphere workers, who are now continuing and expanding ionospheric research in many parts of the Commonwealth and Empire. The Department had gathered together and trained a team of young research-workers, which at the Radio Research Station at Slough and in the National Physical Laboratory at Teddington had done work of the highest quality on other aspects of the physics of radio communication. Appleton had been the first to measure distance by radio waves when he devised, early in the 1920's, a means of measuring

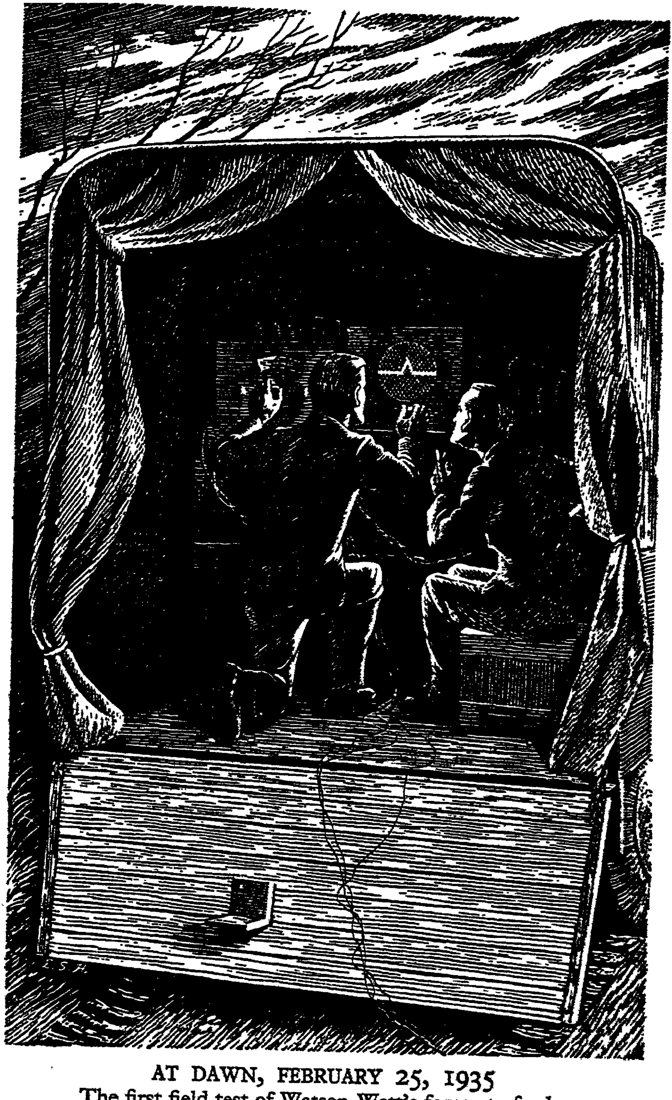
the height of the Heaviside layer, that ionized layer of atmosphere about sixty miles up from the earth's surface. Breit and Tuve's method of working, discovered soon after the Appleton ionosphere team had started, was soon adopted as an alternative and a somewhat more convenient means. But throughout all the Radio Research Board work a cathode-ray tube, now a common piece of apparatus in almost every radar set and in every television set—but, of course, a scientific novelty in the early 1920's—was used to time the radio waves, and thus to ascertain the heights of the various ionized layers.

By timing the pulses of radio energy shot skyward it was found that the ozonosphere layer of atmosphere wraps itself around the surface of the globe at a distance away from the surface of about fifty miles, that the height of the Heaviside layer varies from sixty to eighty miles, that the ionosphere proper starts about a hundred miles up, and that the so-called 'F,' or Appleton, layer, as it came to be known after the head of the little team of British scientists who discovered it, ranges from a hundred and forty to some three hundred miles up. Thus it can rightfully be claimed that Sir Edward Appleton, then of the University of Cambridge, not only succeeded first in *proving* the existence of and measuring the heights of the various ionized layers, but by his radar-pulse measurements incidentally made the very first measurements ever to be taken in radio range-finding.

Watson-Watt was by 1933 Superintendent of the Radio Department of the National Physical Laboratory, and he was the man with vision to realize that this radio range-finding system had potentialities of a limitless degree. It would be entirely wrong to believe that all the preceding work of Appleton, Hollingworth, Gebhard,

Tuve, and other scientists had made radar possible. No circuit then existed of any transmitter or receiver suitable for radar as a navigational aid; nobody could even attempt to draw up a mathematical plan. The spark that brought the world's first radar system out of this gloom of academic experiment was an act of high scientific statesmanship and courageous modesty by H. E. Wimperis, then Director of Scientific Research at the Air Ministry. In the last days of 1934, pressed by Dowding (at that time Air Member for Research and Development of Air Council) to bring new scientific aid to the stark problem of protecting Britain's skies and shores in the event of war, he admitted that the task should not be the responsibility of any one man, but that the finest team of experts available should be called together. Eventually Lord Swinton, who was in 1935 Secretary of State for Air, appointed a committee consisting of Mr H. T. (now Sir Henry) Tizard and Professor A. V. Hill, with Professor Patrick Blackett to help them, and with Mr A. P. Rowe (later to become famous as the head of the Malvern Telecommunications Research Establishment of M.A.P., where so much wartime radar apparatus was devised) as Secretary. The committee found the problem tremendous, and turned to outside experts with a number of long-shot suggestions, even including the possibility of a death-ray!

So, in 1935, Watson-Watt was approached by a member of the committee, and after laughing away the suggestion of a death-ray as an aerial weapon was asked for his views. While admitting that he took a poor view of the chances of a death-ray, and that his own memorandum *The Damaging Effect of Radio Beams* was not intended to be read as a monograph on death-rays, Watson-Watt completed his report with the optimistic note: "Meanwhile attention is being turned to the still



AT DAWN, FEBRUARY 25, 1935
The first field test of Watson-Watt's forecast of echo.

Note. The drawings are merely illustrative, and are not to be considered accurate in detail.

difficult but less unpromising problem of radio-detection as opposed to radio-destruction, and the numerical considerations on the method of detection by reflected waves will be submitted."

This, in fact, was done. The world's first practical radar scheme was drawn up on paper as a piece of pure mathematics and scientific reasoning. Without even bothering to draw a circuit diagram, Watson-Watt showed how radar could be made to work. This is an outstanding example of pure reasoning over practical proof, but the responsible member of the Air Council was not impressed, and said in effect, "Numerical considerations can be pretty much what scientists like to make them. Let's have a demonstration." So out of these discussions, which no doubt were often conducted not without rancour and high feeling, arose the necessity to produce the world's first practical radar set, and thus to show if Watson-Watt's figures were right.

So on February 25, 1935, one junior scientific officer of the radio department of the N.P.L., with one laboratory assistant who could also drive a lorry, took a special receiver and cathode-ray tube to a site near the short-wave station at Daventry. By dawn on the following day the apparatus was working, and Mr A. F. Wilkins was able to pick up reflections from the Daventry station, tiny packets of radio energy being echoed back from aircraft flying near. Mr A. P. Rowe, watching on behalf of the Air Ministry, was able to report that "in the circumstances the result was much beyond expectation." What he had actually been able to see on the cathode-ray tube inside the lorry was the tiny 'blip' (a deflection of the time-base line at one point) caused by reflection of the Daventry signals from Heyford aircraft flying in a certain direction, within eight miles. From this tiny beginning grew radar.

Next day the Air Ministry committee was considering Watson-Watt's full report, *Memorandum on the Detection and Location of Aircraft by Radio Methods*. It was still only a paper plan, but in view of controversies which have since arisen about the credit for pioneer radar work, it is interesting to note that this 1935 "Top Secret" report to the Air Ministry proposed direction-finding, height-finding, 10-metre work, and the need for a radar identification system, which became essential when war came, and which was to become world-famous as 'IFF' ('identification, friend or foe'). The 1935 report also based future progress on pulse technique, which, of course, did become general, and also referred to continuous-wave and to frequency modulation as alternative methods. Both have since found wide new applications, the German fighting forces using frequency modulation considerably, and more recent non-radar navigational systems have used continuous-wave transmissions for range-finding.

A. F. Wilkins, who had featured in the Daventry experiment, went on to develop IFF, while another young member of the National Physical Laboratory, E. G. Bowen, started pioneer work in airborne radar. The Battle of Britain, of course, was the first big wartime operational test given to the chain of radar stations which had begun to function around part of the British coast by March 1939, when the Germans marched into Prague. With the Battle of Britain also we associate the name of Sir Henry Tizard, who initiated the practice of radar 'controlled interception' (the scheme for guiding night fighters against the enemy by radar direction from ground stations), and it was Sir Henry who led the British Mission to Washington in the crucial war year of 1940, when Britain communicated to America the secrets of all our work on radar, before America decided

to enter the war. Informed witnesses of that event affirm that America was astonished at the generosity of the gift conveyed by Sir Henry's mission, that she was amazed at the progress our scientists had made in branches of physics of which our transatlantic colleagues had almost no knowledge, and that the nation-to-nation gift of radar was the greatest single act of friendship between the English-speaking peoples.

Progress in radar, even for war application, was by no means near the end, however. American and British teams worked together. Dr D. Taylor worked on a branch of ground-control using as the radar eye the ingenious 'PPI' ('plan position indicator') cathode-ray tube, described later in this book. Radar was adapted to searchlights, the system being largely the work of L. H. Bedford, of the Cossor organization, Harold Lander, and W. S. Eastwood. Before the War Dr W. S. Butement had been working on radar to locate ships as targets for coast-defence artillery, and had made very great progress in systems which are now not difficult to adapt to the needs of peacetime shipping. At the same time Mr P. E. Pollard was proving that radar range-finding was more accurate in dealing with aircraft than were the big optical range-finders. C. E. Horton and J. F. Coales made noteworthy contributions to radar which eventually played an important part in radar-directed guns which sank the *Bismarck* and the *Scharnhorst*. E. G. Bowen, who had done the pioneer work on airborne radar, and R. Hanbury-Brown were two of the British scientists prominent in the development of airborne radar to locate submarines.

All this successful development is now, of course, only war history, and is apt to be lost in the great accumulations of records of international strife. But this is an appropriate time to reflect that what these scientists gave

the world, under the stress and emotion of world war, was a series of discoveries each of terrifying potentialities, and we must learn to harness them for peace.

But all this work of the pioneers was only a beginning. From the early 1938 days it had been realized by Watson-Watt and his co-workers that greater accuracy was needed. Nothing but a narrow beam of radio waves, instead of the 'floodlighting' technique, would suffice; this meant higher power, to concentrate the beam, greater sensitivity at the receiver, and a much shorter wavelength. Early radar had been effected with transmitters on 50 metres, then 12 metres, and subsequently right down to 2 metres; but this was yet not short enough to produce a pencil-like beam, for reasons we will consider in a later chapter. Existing apparatus was working at about its minimum wavelength; valves and associate apparatus could not handle higher frequencies. Fortunately we were well placed as a nation to deal with the problem, for from March 1939 ninety of our leading physicists, men who had spent much of their lives in the solving of abstruse problems of splitting atoms and in electronic research, had been attached to the chain of coastal radar stations. They decided that we should probably have to employ wavelengths as short as 5 or 10 centimetres, and certainly less than a foot in length. There was then no radio valve which could produce such high-frequency oscillations.

Professor M. L. Oliphant, of Birmingham University, and Dr H. W. B. Skinner, of Bristol, inspired their co-workers by their insistence upon the need for centimetric waves, and by their own experimental skill. A tremendous drive followed, until in July 1940 Professor J. T. Randall, of Birmingham, produced a magnetron, which was the first high-power generator of centimetre-length waves. The magnetron remains the very heart

of much modern radar transmitting equipment. This new tool was eagerly seized upon by radar researchers, the only setback (for this was during wartime) being that caused by some operational heads of the Fighting Services, who recognized the vital need for the magnetron, but refused to allow aircraft carrying the new valve to fly over enemy territory, lest one complete magnetron be disclosed in a crashed aircraft. A difficulty was that the magnetron construction employs a high-tensile casing, almost indestructible and certainly not likely to be damaged by the self-destruction fuses fitted to other radar apparatus to destroy it if it fell into enemy hands. At last this prejudice was overcome, and centimetre-length radar became general in the air, on land, and at sea. The magnetron was supplemented by an equally novel receiving valve evolved by Dr R. W. Sutton.

There are peacetime applications to many radar devices conceived during war, notably H2S, Gee, Oboe, and Rebecca.

H2S, as we shall see later in this book, is the true 'television' of radar, showing in an aircraft at night or in fog a picture of the unseen ground over which it is flying. H2S made the ruins of Berlin and Hamburg its monuments, and now has beneficial peacetime applications in map-making of the new world. A. C. Lovell, Professor P. I. Dee, and Dr Skinner were largely responsible for H2S, and Denis Robinson made his contribution to a system of H2S 'television' for locating ships at sea. Gee, the long-range navigational system which made mass raids possible, and which is now a most reliable system of radar navigation on civil air lines, was developed by R. J. Dippy (who also gave his name to the Dippy oscillator, an important radar circuit), with the help of C. C. E. Bellringer. Oboe, the companion long-

range radar navigational aid, was the work of F. C. Williams, A. H. Reeves, and F. E. Jones. Rebecca-Eureka, out of which has come many modern navigational radar aids, was devised by F. C. Williams and J. W. S. Pringle.

The story of how radar came to be invented must also include the names of scientists such as Dr W. B. Lewis, of Cambridge, who at the Malvern research centre contributed to almost every step of radar progress, and of J. A. Ratcliffe, of Cambridge, and Dr L. Huxley, of Nottingham, who together built up Britain's first 'radar university,' wherein other scientists and workers could learn how to work and develop radar. There is also the valuable technique of radar trainers and synthetic apparatus developed by G. W. A. Dummer, devices which enable pilots and radar operators to 'fly' thousands of miles by radar without moving from a seat at a desk; these trainers allow operational men and women to learn their task through robot apparatus which simulates travel by sea and air. With these radar devices for training risk of human life is reduced, and much money time, and fuel are saved.

It was not possible to tell this story of radar while we were all bound by the essential needs of wartime secrecy; credit could not be given to the men who really did the jobs that mattered. Quite early in the post-war years there was hasty, ill-considered, and premature publication, on both sides of the Atlantic, of much material purporting to tell how radar works and who made this miracle possible. So vast is the radar field and so great its potentialities that it is really to be wondered that there was not even a bigger spate of tendentious material and consequent wrangling. No amount of familiarity with radar can blunt your appreciation of what has been achieved; from the small beginnings of Appleton's

workers it has become an engineering enterprise of great diversity and magnitude, and it is still growing.

Let us now step aside from this race of progress and study the basic principles of radar itself.

II. SHORT, SHARP SHOUTS

ALTHOUGH RADAR IS NOT JUST A MATTER OF SENDING out a pulse of radio energy, picking up the echo, and measuring the time that has elapsed, we shall find the whole picture of radar much easier to visualize if we look first at the pulse system, which is really only a series of short, sharp shouts by radio.

Those short, staccato pulses are the means by which radar can see farther than the human eye, even in the best visibility, and are one of the reasons why radar's vision is unaffected by fog, night, rain, or cloud. The one factor common to all true radar systems so far is our knowledge of the speed of propagation of radio (electromagnetic) waves in space. Scientists and cynics take some delight in the fact that we have discovered radar and worked near miracles with it basically through our knowledge that radio waves travel with a velocity of 186,240 miles a second; but we do not know anything of the medium through which they travel (we call it 'ether' for the want of a better understanding), and there is, indeed, another school which believes that there are no wave-like vibrations in this unknown ether, but there is actual transmission of little packets of electrical energy. Whatever it is, waves or spurts of electron activity, *something* travels with a speed of 186,240 miles a second, and for the purpose of radar measurements that is all that we need to know. How are we going to relate this knowledge of the speed of radio waves to our practical problem of locating, say, an aircraft in the night skies or a ship in fog?

'Radar' is a war-born word, coming out of the British

'radio-location,' which not only was considered to be insufficiently streamlined for the wonderful new technique, but was not expressive. Radar to-day is much more than 'location.' So the word 'ra-dar' was coined to describe 'radio detection and ranging,' though it would be truly more descriptive if the phrase were 'radio direction-finding and ranging.'

Now radio waves travel at the same speed as light waves, and, indeed, share many of the same properties. They can be reflected and scattered; they can be split up or combined. To the casual layman the 'speed of light' is much the same thing as 'instantaneous,' but the whole science of radar is built up on the microscopic time intervals which elapse—intervals of so much less than a second that we split the divisions up into 'milliseconds' (thousandths of a second) and 'microseconds' (millionths of a second). Just why such a fine division is necessary you will easily see.

For a rough example let us say that the speed of radio waves is 186,000 miles a second. One single burst of radio energy is transmitted, and it darts out into space in all directions, one tiny fraction of this energy striking the metal substance of an aircraft. The radio wave, being similar to light (only much longer in wavelength), is reflected in a more well-defined manner than if a pencil of light from a searchlight were to strike the aircraft and send a reflection back to the ground.

If we had some special sort of electric stop-watch, and timed the echo, we might find, for the sake of example, that the echo came back to us, faint but accurately, in $\frac{1}{500}$th part of a second. That is the *total* time taken for the radio wave to leave our aerial, traverse space, hit the aircraft, and be reflected back through a receiving aerial to our electric stop-watch.

We can easily see from this that the total distance out

and back must be $\frac{186{,}000}{500}$ miles, which is 372 miles. If we halve that for the single journey we see that the aircraft is 186 miles away from our station. It would be very convenient if all radar calculations were as simple as that! We shall find, however, if we go sufficiently deep into radar mathematics, that the figures of the subject become extremely involved, especially where we find ourselves on the threshold of nuclear physics. Like astronomy, radar is a subject which can be studied purely from the aspects of mathematics, although most of us find it more entertaining to ponder on the mechanics of the subject than on the complex arithmetic.

You can work out for yourself several typical examples of radio-wave speed and object distance. You will find, for example, that 186 miles represents a time-interval of 2 milliseconds, 9·3 miles an interval of 100 microseconds, 1 mile 10·7 microseconds, and $\frac{1}{10}$ mile 1·07 microseconds. I give these figures because for all practical purposes they cover the present range of radar, from about a tenth of a mile up to 186 miles, by direct reflection. There are several long-range systems, such as Loran, where radar is effective up to many hundreds of miles, but here the technique is somewhat different, and as these long-range systems are described in a later section of this book we can neglect them here in our basic discussion of radar.

If we are to time anything by radio waves, however, it will be obvious that we shall need some stop-watch which can deal with very minute periods of time, ranging from about $\frac{1}{500}$ second down to about a millionth of a second. Not many years ago the possibility of such a stop-watch would have been scoffed at by all serious thinkers. In a period of about fifty years radio, as we know it to-day, was developed; in various stages came the valve, the pulse transmitter, the cathode-ray tube

(which is now the basis of our electric stop-watch), and, finally, the radar system, which would have been just a piece of neat mathematics in Sir Robert Watson-Watt's notebook, quite undemonstrable because we had no apparatus for measuring millionths of a second, but for the fact that when we discovered the precious secret of radar there was the electronic 'stop-watch,' ready for a whole new series of discoveries.

Many people will have seen a cathode-ray tube in use in a television set: the greyish-green glow is familiar both in laboratory test gear and in entertainment television. But in television we see, normally, the complete picture formed on the end of the tube. We do not see the tiny pencil of invisible electrons which leave the cathode at the 'small' end of the tube and trace a pattern on the fluorescent screen at the larger end. Just how the tube works we shall see in a moment, in a subsequent chapter. But for the present we can consider the tube as being evacuated, leaving a nice empty space in which there is a pencil of electrons which can be made to sweep about over the screen end of the tube and trace out a pattern on the fluorescent surface. The beam of electrons can be made to sweep across or round the screen, rather like the way in which the hands of a clock sweep round the face. Just as the second-hand of a clock completes the sweep of the dial in sixty seconds, ticking its way around the chapter ring, so the pencil of electrons in the tube can be made to trace a pattern in any interval of time. We cannot swing the hands of a clock much faster than, say, one tick every second, because there is inertia, and even the most carefully balanced clock hands have an effective mass. But there is no weight in the pencil of electrons, no lag, and so the beam can be swung backward and forward with the speed of light. The pencil of electrons can be focused,

in a manner very similar physically to the focusing of light, and can be made to produce a single fluorescent spot of light at the end of the tube. If it is caused to move backward and forward over the same path the spot of light will travel up and down, or from side to side, and if the beam is moved very rapidly, then the eye will be unable to follow the single spot, and persistence of vision will make us think that there is just a single line of light. Indeed, for very many practical purposes in radar, later on, we shall regard the image as one single line of light, perhaps with various patterns emanating from it, but we should never forget that it is not really a line at all, but the passage of a single spot.

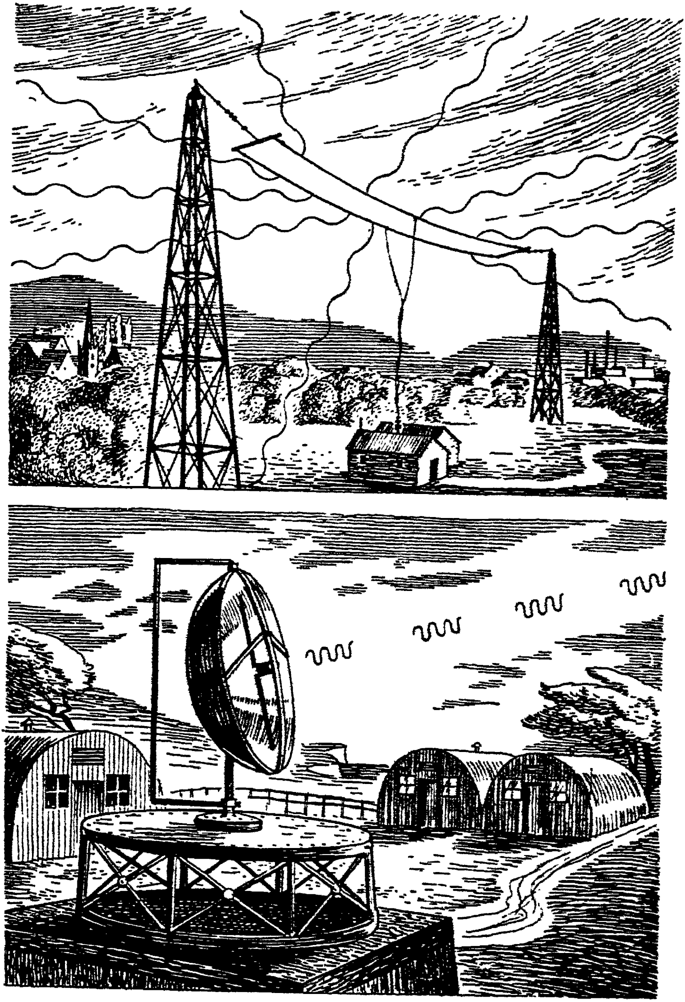
Now we can use a cathode-ray tube like this as an electronic stop-watch, and wire it up to our transmitter and receiver. This is just what we do in radar, and as the cathode-ray tubes comes so frequently into our working, let us get into the habit of naming it by its initials, C, R, and T, as radar engineers do.

We can switch on our CRT and adjust the speed of the electrical device which is pulling the beam back and forth across the tube so that the beam moves across the screen, leaving a single line of light, in $\frac{1}{500}$ second. This line will represent the time taken for a radio wave to travel 186 miles out and back. So we can write 0 miles on the screen at the beginning of the line and 186 miles at the end of it. We then look at the apparatus moving the spot of light, and make sure that it is causing it to move at an absolutely constant speed, so that the spot does not travel faster along one part of the apparent line than it does along another. Of course, we could never do this with a mechanical lever, for it would have inertia and would take an appreciable time to get going at the start of the line, and would need to be slowed down before the end. But our electron lever has no appreciable

inertia, and we can start it right at the beginning of the line at full speed, stop it effortlessly at the end, and send it back again at the same speed. If we adjust it thus, at constant speed all along the line, we can regard it as a true scale. We should be quite justified in marking and subdividing the whole scale into miles, starting at 0 and ending with 186.

Then we adjust our apparatus again and 'black out' one part of the line. The spot starts from the left, travels to the right, stops, and instantaneously begins its travel back. This is the part we suppress electrically. Our electron beam thus traces the line, but the 'flyback' is blacked out for the return journey. Then $\frac{1}{500}$ second later it starts a new journey in exactly the same place, unless meanwhile we do anything to divert the spot into another direction; and that is just what we do. We put two plates, or a magnetic coil depending on the associate apparatus, near the line of the beam, and wire these plates or the coil to our radar transmitter and receiver.

The transmitter is adjusted to broadcast what is really not a continuous note, but a series of short, sharp 'pips' of energy. As each pip goes out into space a circuit linked with the CRT momentarily pulls the spot of light down out of its straight-line path, just as it is starting on its journey. This happens many times a second, because in sending out radio waves for a radar job we must be careful to keep them in very small bursts or pulses, not lasting more than a few millionths of a second. The reason for this is that if the pulses lasted for a longer time they would drown the returning echo. Pause for a moment to think what you do when you shout against a hillside and try to get an echo. If you keep up a sustained yell you cannot hear the echo, but if you make a series of short claps or staccato shouts



THE DIFFERENCE BETWEEN BROADCASTING AND RADAR

Broadcasting sends continuous waves in all directions; radar sends short pulses of wave energy in one direction.

Note. The picture is merely illustrative, and is not to be considered accurate in detail.

you hear each individual echo coming back, and this applies equally to radar pulses.

The returning radio echo is picked up by highly sensitive receivers and made momentarily to deflect or dip the electron beam in our CRT, so on each occasion the spot—many times a second—is pulled out of its path. Persistence of vision is such that the human eye sees the spot pulled out of its path at the beginning of the line, causing a deep, sharp V-shaped depression, or 'blip,' or 'break,' and a much smaller blip some distance along the line, marking where the received echo has registered its homecoming, on the CRT light-line.

We have already marked off a scale of miles above the line of light, so by reading the number of miles opposite the echo blip we can tell instantly how far away is the aircraft. Think back for a moment, and you will realize that there are two processes going on here simultaneously. There are the radio pulses being shot out into space at a speed of roughly 186,000 miles a second, and if an aircraft or a ship is 186 miles away, then we shall find that the pulse goes out and echoes back in $\frac{1}{500}$ second. If the object is not so far away as 186 miles, then, of course, the echo will come back more quickly, and if we could accurately measure the time we should know the distance.

Simultaneously we have the electron beam in the CRT being pushed over from one side of the tube to the other in $\frac{1}{500}$ second, the light-spot thus taking the same period of time for its job as does the radar pulse which causes the echo. By deflecting the light-spot as the pulse goes out, and by deflecting it again in a blip as the echo comes back, we can use the actual distance along the light-line as a measure of time, and thus of distance between the radar station and the far object. As this is the basic principle of many radar systems,

and of the use of a CRT for basic radar display, you would be well advised to read the last two pages very carefully over again, not taking any statement for granted, but making sure you have a thorough grasp of how the CRT acts as our electron stop-watch.

Of course, the process is continuous. Many pulses are being transmitted every second, with sufficient time interval between them to allow each echo to return from the greatest distance we have set our radar apparatus up to measure. The electron beam is also sweeping up and down the line many times a second, and is being deflected by a constant succession of returning echoes. All this happens far too rapidly for the eye to see anything but a steady, glowing line of light with a couple of blips. If the aircraft is approaching the blip will move slowly in the direction of 0 miles. If it is going away it will move towards 186 miles. In this way the movement of the aircraft can be watched continuously. If we are picking up echoes from more than one aircraft, then we shall see a number of small echo blips along the line. Some may be moving away, some home.

Although this is 'basic' radar, it is, indeed, just the sort of elementary display which was possible when Mr A. P. Rowe, watching on behalf of the Air Ministry, saw radar reflections from an aircraft near Daventry in 1935. Roughly speaking, we can see how far away the aircraft is from the transmitter, but, of course, to be of any real use as a navigational aid radar must do far more. We can increase our accuracy, first of all, by realizing that the *exact* distance between the two blips (marking the transmitted-pulse instant and the echo-return instant) is the distance between the leading edges of the two V-shaped blips. We must not cause confusion by measuring between, say, one leading edge and one lagging edge. We must take our measurements from the

leading edge in both cases, which is the *precise* instant of depression of the CRT spot out of its time-base line.

We must not be content to assume that the light-spot is travelling at a constant speed over the line; if it should for any reason move faster at one part than at another it would be like using an electric ruler in which the inches were unequally marked along the straight-edge. To make absolutely sure that the spot sweeps at the appropriate speed many radar receivers incorporate a unit known as a calibrator, which is perhaps more conveniently and euphoniously known as a 'Cal.'

The Cal is a number of oscillator circuits giving a series of direct-current pulses, and we can apply these to the plates or coils of the CRT to move the light-spot out of its track at intervals. These blips can be separated by any prearranged time-intervals, such as $\frac{1}{9312}$ second, which correspond to increments of range equal to 10 miles. If we set the Cal up like this and switch it on a series of bright lines appears along our main time-base line on the CRT, giving a sort of fence or tooth-comb effect. We should not forget that although this tooth-comb appears to be stationary, it is really only the electron beam being moved out of its track several times on each trace, at precise intervals of time. But we are now at this point not so much concerned with time as with distance, and if we adjust the Cal to produce a spike of light on the time-base every $\frac{1}{9312}$ second this will correspond to a distance of 10 miles on our electron 'ruler.' So we call Cal pips thus set up our '10-mile pips,' or, if we run the Cal circuits twice as fast, there will be twice as many spikes of light, and they, of course, will mark 5-mile intervals. On some very precise radar apparatus we even check by using 1-mile Cal pips. The calibrator is just a check. We do not switch it on, normally, when the radar is operational, but test it every

now and then to ensure that our time-base—our apparent line of light on the CRT—is being covered by the light-spot at a constant speed throughout. If there were any variation in the speed a little thought will show that the Cal spikes of light would not be evenly spaced like the teeth of a comb, but would be closer in groups at one part of the line than at another. This is, in faulty apparatus, a very common radar effect, and is cured, as we shall see later, by adjusting the resistances, condensers, or other circuit values which result in the CRT electron beam being pulled across the tube. When we have the whole thing nicely set up, with Cal pips evenly spaced, we say we are working 'on a linear time-base,' which simply means that if we drew a graph of time against speed of the electron beam the result would be a straight-line figure.

At this stage it is worth deviating for a moment to consider some other familiar radar expressions and tricks. The display so far described is, as we can see, a rather primitive one. We are faced with a great blip of light showing where the transmitter pulse is being sent out, and a fainter one, or several fainter blips, showing echoes received back. If the transmitter pulse is very big it will hide some of our faint, very close echoes. As the transmitter pulse serves no real purpose here we can dispense with it, and in many radar systems we do commonly black-out the blip. The transmitter 'triggers off' the rest of the radar equipment, and just at that instant the light-spot in the tube is cut off. This results in the beginning of the 'trace,' or line of light, not being permanently cluttered up with the bright, unnecessary blip caused by the home station, which may confuse the accurate spotting of weak echoes near home.

We are still troubled with echoes from fixed objects near by. Fixed features of the landscape—tall buildings,

hills, headlands, and masses of trees—all give reflections of the radio-energy pulses. Operationally they can be a nuisance, because they tend to clutter up the line of light at places where we might find echoes of essential objects. The most that can be said for permanent echoes—or 'PE's,' as they are called—is that they do not move along the trace (unless a building or hillside decides to perambulate), and so can be picked out. The real trouble caused by PE's is that the great majority of them are found near at home, and thus even though we suppress the blip caused by the transmitter the first part of the trace is not very helpful to us, because it is confused with a mass of superimposed short-range echoes. This group of PE's, colloquially known as 'clutter,' really determines for us the minimum range at which we can use any one type of radar gear, because it is quite unreliable to try to read echoes through the mass of clutter.

Another familiar radar term is 'strobe,' a partly manufactured word which accurately describes a very useful brightening device on the CRT. So far we have talked of moving the electron beam across the tube, producing the straight trace of light, and of deflecting it for Cal pips and signal echoes. But, of course, we could also arrange to increase or decrease the intensity of the beam at any minute instant, thus brightening or dimming the fluorescent spot. If we arrange one of these little bursts of brightness to coincide with, say, the downward deflection of the spot on one of the Cal pips, this will happen dozens of times a second, or thousands of times a second, or at whatever speed we have set our spot of light to move. And, again, that good friend of radar, persistence of vision, will make the light at that one spot appear brighter. Or, in radar jargon, we have 'strobed' the spot.

By adjusting the values of condensers and resistances we can arrange this strobing to take place at any position we like along the trace; in fact, it is very useful to have a fine variable control, so that we can slowly move the brighter, accentuated portion along the time-base line and leave it set at, say, an echo we wish to emphasize above anything else. Operationally the strobe is a very useful control on many types of radar receiver, for by it we can use the brightened spot as a marker to draw, say, a colleague's attention to one particular echo of several in a group along the time-base, or it can be used as a selector, to brighten one echo so that the human eye becomes more easily fixed upon it.

Anybody who has seen a radar outfit in action will know that what we have so far assumed—a nice clean line of light for our time-base and neat echoes, or blips, along it, indicating the positions of objects giving radio reflections—is a theoretical state of perfection never achieved. In addition to the deflections of the time-base caused by received echoes it is obvious that, as the electron beam of the CRT is actuated by our radar receiver, any other sort of signal, pulse, or disturbance in the receiver output circuit will also tend to deflect the beam. Every listener to an ordinary broadcast receiver knows that no matter how well designed is the outfit there is always some appreciable background hum from the power unit, or amplified hiss coming through from the high-frequency side. Valve noise, resulting from many combinations of mechanical and electrical variation inside the valves, also adds to the slight background noise, but in aural reception the noise can be filtered out, for all practical purpose, so that it does not offend the ear. This noise presents itself on the CRT of a radar receiver, however, and it is not so easy to trick the eye as the ear. Where we have a display of blips

along a straight-line time-base noise shows up as a shimmering effect along the whole time-base, having the appearance of a rapid series of random deflections; in many radar systems the colour of fluorescence on the tube-end is green, so this noise looks for all the world like a shimmering layer of grass, and in radar colloquy is, in fact, known as 'grass.' As the gain of the receiver is turned up the background hiss increases, and the layer of grass along the time-base line deepens. On most equipments, therefore, we have to choose a setting where we get sufficiently strong echoes received back from our distant object without the display being cluttered up in a mass of grass. Unless an echo is strong enough to cause a blip on our CRT deep enough to show above the grass layer we shall miss it.

Radar transmitters, naturally, are complicated pieces of apparatus, because they must be designed to send out a pulse of tremendous energy thousands of times a second, and must then cut clean off, so far as outgoing oscillation is concerned, so that the pulse can travel out into space and, if it hits any distant object, have ample opportunity to be cleanly reflected home again before the next pulse goes out; and this process must be continued hundreds, perhaps thousands, of times a second. But we shall find the working principles of radar simpler to follow if we begin at the receiver end. So let us go on to see what we need in a radar receiver, and how we shall display the results on a CRT.

III. THE ECHO COMES HOME

SOME YEARS AGO QUITE A NUMBER OF PEOPLE VISUALized that radar might be possible if only we could devise a transmitter powerful enough to send out pulses which could be echoed back to earth, and build a radio set sensitive enough to receive them. To-day radar has become so complex that we very often forget what tremendous strides have been made in these two most important directions. A number of radio sets do not give satisfactory performance even when they are used for reception direct from a broadcasting station; that they should pick up *reflections* of such signals is still, to many people, inconceivable. Yet that is just what is happening day in, day out, with hundreds of thousands of radar navigational and beacon stations for shipping and for civil and military aviation, and we do take this miracle very much for granted.

The echo comes home; but we do need a receiver much more sensitive than the average broadcast set in order to pick out the echo. Also, as we saw in the preceding chapter, the mere reception of the echo by itself is not sufficient: that would tell us there was, indeed, a reflection from some object, but would be no help at all towards locating its true position. We must, on our CRT light-line, have as markers the blip of the transmitter (or the equivalent of it, if we desire to black-out the visual display of this pulse) and the blip of the echo, so that we may be able to see the difference in time, and thus in miles, between them. Therefore we want to arrange the transmitter to 'trigger off' the receiver at each instant when a pulse goes out into space, and the

time-base line will be formed in such a time interval that the homecoming echo can be seen. Then the whole thing switches off until the next pulse goes out, perhaps $\frac{1}{500}$ second later. Transmitter and receiver have thus to work in unison, and for practical purposes it does not matter much if we cause the transmitter to 'trigger off' the receiver, or if it happens the other way round.

Now so far as the receiver is concerned, we must expect it to pull its weight in two directions. At the greatest ranges over which we are likely to need radar coverage we must expect it to show an adequate signal-to-noise ratio on echoes from all reasonable targets. Obviously we could design a very large set, full of amplifier stages, the overall gain of which would be great, but the background noise would be such that the heavy layer of grass on the CRT would hide the echo.

Secondly, the gain of our receiver must be enough to cause the beam of the CRT to be deflected. Physicists can prove that all signals are received on all aerials; the simple crystal set, if tuned to about two metres, might be able to receive radar signals; but there would be no point in that sort of reception, as the amplification would be nil, and we should see or hear nothing.

Reverting to 'grass' for a moment, we are faced with the fact that receiver noise is of multiple origin, but quite a lot of high-frequency noise is picked up in the aerial and the transmission system linking aerial and receiver; the rest, such as valve noise (or electrode noise, as it is sometimes called), crops up in the initial stages of the receiver. Signal-to-noise ratio can be measured quite easily on a radar set, for it can be done with an inch tape.

When we have switched on the set we notice that the steady noise causes a layer of grass on the tube, and although it will appear to be shimmering slightly, we can, to within about an eighth of an inch, make a prac-

tical measurement of this with a straight-edge. Then, when we turn the aerial array towards an object giving an echo, we shall see the spike blip of light on the CRT standing out above the grass, and thus again we can measure the length of this echo. The two measurements can be compared as a ratio, and this ratio of signal deflection (echo-length) to the mean noise-level is called the S/N ratio, or the 'Z factor.' Thus the limit of reception on any given radar set is when the Z factor = 1, for then the greatest echo is no longer than the average depth of grass. Incidentally, the noise-level in a radar receiver is proportional to the square root of the receiver's frequency-band width, and so circuit-designers have to choose tuned circuits in the high-frequency stages which have certain characteristics of band-width.

Now we see that a good radar receiver should have a satisfactory Z factor, so that noise does not drown echoes, and its output should be powerful enough to deflect the CRT beam on the weakest echoes ever likely to need diagnosing.

For most purposes we use a superhet, and it would be very desirable if we could employ a receiver having several stages of high-frequency amplification before the mixer stage, so that we should have plenty of amplification at signal frequency before stepping up to the intermediate. It is not possible for us here to go into the general questions of receiver design, and for the purpose of discussing radar technique we must assume at this stage a general knowledge of broadcast reception technique up to superhet standard. A superhet is essential for most radar use, and it can be given narrow bandwidth by locating band-width controls in the intermediate-frequency (IF) stages. Many radar receivers working above wavelengths of 10 centimetres have several HF stages at signal frequency, but for radar

working below 10 centimetres we have to discard these initial amplifiers. Of course, as we shall see in due course, a number of tricks, strange devices, and novel valves are used even in radar systems of the more conventional wavelengths (around 2–10 metres), and the newcomer, on making a close inspection of the whole receiver, may be puzzled at circuit values. But on the whole the arrangement is normal, and the layman is apt to marvel at the comparative simplicity, or at least conventionality, of these radar receivers. It is not until we start to use very high frequencies, resulting in wavelengths of 10 centimetres and less, that the new technique is startling to one grounded in conventional broadcast methods.

For most radar outfits it is more convenient to talk in terms of frequency than of wavelength. You will find it easy to translate one term into another if you recall that 14 Mcs (megacycles) represents 20 metres, 28 Mcs 10 metres, 56 Mcs 5 metres, 112 Mcs $2\frac{1}{2}$ metres, and 224 Mcs $1\frac{1}{4}$ metres. Those figures will act as signposts for other mental calculations.

The early chain warning system of radar stations in Britain used what radar experts now regard as 'very long' wavelengths, between 10 and 13 metres. The special Chain Home Low equipment for detecting low-flying aircraft worked on 200 Mcs. With radar carried in the air quite a number of different problems present themselves. The original airborne aircraft-interception apparatus used a diminutive form of ground radar, and worked on about 200 Mcs, but very soon the new centimetre technique sprang up, on the British discovery of the magnetron, and the very ingenious radar systems such as H2S came into being, using such short wavelengths as 3 *centimetres*, a very far cry from the 300-*metre* band used by broadcasting stations.

We have spoken of the transmitter 'triggering off' the receiver, and of pulses being sent out; but much depends on the type and frequency of triggering and the shape of the pulse. There is a parallel here with our former simile of short, sharp shouts against a hillside to produce an echo. A steady, booming sound will not produce a sharp echo, because such a noise begins slowly, comparatively speaking, and ends slowly. We need a 'sharp-edged,' staccato sound to make the clean echo. By wiring our CRT to appropriate parts of our transmitter we can deflect the spot in exact sympathy with the type of wave-form being produced by voltage changes in each circuit. We can actually see the shape of the outgoing pulse, and on most equipments it will show up in the form of U or V. The straighter and more upright the sides, like the figure ⊔, the sharper will be the start of the pulse and the more sudden its cessation, and this gives us the radio version of the staccato shout. This pulse can be formed by combinations of radio oscillating circuits, the first of which produces a sine wave, or similar wave-form, with rounded edges and faces; and in subsequent circuits the wave-form is sharpened and straightened until it becomes almost what is known as a square wave. Most of the pulses in radar circuits are, in fact, varieties of square waves, very different indeed from the sine-wave forms handled by the stages of broadcast receivers. Conversely, a loud-speaker wired to the output of a radar set produces a particularly obnoxious noise, the speech-coil of the speaker vainly trying to follow the sharp impacts and cut-offs of the square-wave pulses.

So now let us have a look at our complete radar chain of apparatus. We need a modulator ('Mod') to produce a nice, sharp-edged pulse. The usual Mod is an oscillator and a series of distorter valves, all striving to

produce a square wave out of a sine-wave oscillation. The output of this Mod is arranged to produce a pulse of energy of a suitable width, recurring at the desired frequency. The pulse-width determines the actual length of time which the transmitter is switched on at each pulse —in other words, the *duration* of our short, sharp shout. The degree of recurrence of the pulses is known as the 'pulse recurrence frequency,' or PRF, and, of course, it is really the *number* of shouts we give each second. All this is controlled by Mod circuits, in which by varying condenser and resistance values we arrange to produce the right shape of pulse, for the desired period of time (pulse-width), and the necessary number of times per second—the PRF.

The output of the Mod is fed into the transmitter. As the Mod is a central source of wave-producing circuits the same Mod is used in some radar equipments to produce wave-forms both for transmitter and receiver. The Mod may thus be used as a sort of electronic key to switch on and off the transmitter, as well as controlling fundamentals of the receiver and the movements of the CRT light-spot Its primary job, though, is to turn on the radio-frequency oscillator of the transmitter, making it oscillate violently for a millionth of a second or so, then turning it off equally sharply and keeping it in repose until the time for the next burst. During those minute silent intervals the energy is reflected back from the distant object, and our receiver has given one spurt of its CRT display.

Design of the Mod and its pulse-shaper has been one of the intricate tasks of radar experts. Later on, when we look at the pulse system in more technical detail, we shall see just why it is a difficult job. But for the moment we can regard the Mod as a series of circuits producing a gigantic square-shape wave with steep sides giving a

sudden beginning and ending to the oscillations of the transmitter.

Our radar transmitter is apt in physical dimensions to be a surprise to the enthusiast familiar with commercial and broadcast stations. Here we have stations putting out, say, 100 kilowatts, and taking up, perhaps, an acre of ground-space, using giant water-cooled valves and enough machinery to fill quite a respectable public-utility power-station. But in radar we use apparatus that will almost fit into a suitcase, and yet transmit with a power of several hundreds of kilowatts! The reason is that with pulse transmission, as the name implies, we are not transmitting continuously, but in a series of giant pulses. The transmitter can be heavily overloaded during the minute period of the pulse, for there then follows a comparatively long interval of time when the oscillator is quiescent and doing no work at all. So in radar, as distinct from speech broadcasting (where we usually have a continuous-wave carrier), we can use quite small valves and very economical circuits, overloading them tremendously for minute portions of time. The longer we make our pulses—that is, the greater the pulse-width—and the greater the PRF, the nearer we get to a continuous-wave state of working, and so we need bigger apparatus. In the majority of radar pulse systems the interval of time during which the pulse is on is infinitesimal compared with the long interval of time between pulses. The momentary bursts of oscillation produce a power of several hundred kilowatts. The *peak* power is thus tremendous, but the *average* is usally low. Quite a large radar transmitter may run an average power up to one kilowatt, which in radio transmission is very low indeed, and for the sake of domestic comparison, of course, is only about the power consumed by one bar of a normal electric radiator or by a

toaster. Because of the pulse system and the momentary overloading radar equipments run at powers thousands of times greater than was thought possible a few years ago. The real radar problem, as we shall see, is to design valves, not which will handle more power, but which will oscillate at the very high frequencies which a narrow-beam radar system necessitates.

The next link in our chain is the aerial—the aerial at the transmitting end and the aerial at the receiving end.

For an appreciation of radar technique it is necessary to change our normal conception of the propagation of electromagnetic waves. In a broadcast receiver we use an aerial of an indefinite length and a 'lead-in' of any reasonable proportions to link receiver to aerial, without worrying unduly about the electrical constants of the aerial-earth circuit. This is, of course, the Marconi arrangement, where an aerial and earth (or counterpoise) are connected in series with a tuned circuit to bring the whole system into resonance with the desired frequency.

In the Hertz system we arrange that the aerial system is self-tuned to the desired frequency, and a device known as a feeder line (more colloquially a 'transmission' line, when the conductor links a transmitter to its aerial system) is used to connect the aerial array with the first stage of the receiver or transmitter. There is no need to elaborate on transmission-line theory in this present volume, as it is a normal part of radio technique and has already been adequately covered in *The Amateur Radio Handbook* and in Section R of the Admiralty *Handbook of Wireless Telegraphy*, to mention two outstanding examples.

Now it will be recalled from our knowledge of wave propagation that there is an essential difference between what may be termed earth and non-earth waves; there is also attenuation of the indirect-ray component of the

electromagnetic wave propagation, for the earth's atmosphere is by no means a constant dielectric. Radio waves are attenuated much less in the air than in the earth's surface, and the upper limit is set by the density of free electrons in the ionosphere. The combined effect of such attenuations, and contributory causes, is to set limits to maximum communication ranges at various transmission frequencies. At the lower frequency limit, for example, it has for many years been realized that even for night transmission a frequency of 4000 kcs is the lowest which can successfully be used. Limits at the other end of the scale have not until comparatively recent years been of great interest, for transmission below about 5 metres was not a practical commercial proposition until the last decade or so. But the needs of radar, which compel us to use very high frequencies, have caused investigation to be made into the attenuation limits at extremely high frequencies, and thus it is that for most radar systems we use very short wavelengths, handled by aerial systems which at first appear to follow optical laws more than the normal practice of electromagnetic-wave propagation.

When Watson-Watt first conceived a practical radar system the 'floodlight' system was devised. In this a high-power transmitter kicked a series of pulses out into space in every direction. If an aircraft is within range, then an echo is bound to be picked up by the receiver, and by the usual direction-finding system of right-angle aerials and comparison of signal strength it was thought not to be impossible to plot bearing. As can be imagined, this system was simple in theory, but in practice it presented us with a number of snags, not the least of which was the great waste of power in floodlighting a vast area with pulses when we could effect a great economy if we could beam the energy and make a

'searchlight' of our radar rays. This involved making the transmitting aerial directional, and rotating it, or swinging it over an arc wherein the distant object might be. An equally directional aerial could be used to receive the echo, and, of course, the receiving aerial could be swung in synchronism and in line with the transmitting aerial. The higher frequencies (thus the shorter wave-lengths) we use the easier it is to concentrate our transmitted beam with aerials and reflectors of reasonable proportions. Indeed, when we come right down to wavelengths only an inch or so in length we can employ aerials and reflectors to beam the rays just as we should beam light rays. There is a similarity even in appearance, for the great bowl-shaped 'dishes' of wire-netting and the metal parabaloids used as reflectors are like giant searchlights. Something like the same 'optics' apply, but, of course, we do not use radar waves as short as light waves. The longest light waves, those of red light, are only one-sixty-thousandth part of an inch in length, and the shortest radar waves in commercial use at present are half an inch. Nevertheless the bowl-fire aerials of many radar beacons do behave just as a searchlight reflector would do, and we can beam our outgoing radar rays so that we can detect with an accuracy of about one yard for every mile distant.

Our aerials begin to become complicated; they beam out and bring in the transmitted energy, and must be efficient. All the generated power in the transmitter aerials, for example, must go into the main beam, and not into any of the side-lobes, where it not only would be wasted, but would cause spurious reflections from confusing directions. On ships and aircraft the aerials not only have to be directional for range and height, but often have to be stabilized to cancel out the motions of the ship or aircraft itself.

On land beacons, and with navigational systems such as Gee, the aerials can be fixed, but with certain airborne equipment, such as H2S, the rotation of the aerial to scan and sweep the ground below, and thus to build up a television picture by radar reflection, forms an integral part of the system. One essential of nearly every radar aerial array, however, is that it must have highly directional properties. The main object is to concentrate the beam into as small a space as possible; in fact, the shorter the wavelength we employ (the higher frequencies) the more we approach the state of light, ideal for many radar purposes, where the outgoing beam is virtually only a pencil, a degree or two in width. You can thus picture the aerial system as something like the headlamp of a car, or a highly directional searchlight, broadcasting a pencil-like beam which scans the skies.

With normal frequencies there are two ways of making an aerial directional. We can build it up on the searchlight principle, with reflectors and 'directors,' which are really the electrical counterparts of the similar optical systems. If we are using centimetric waves we can make our reflector so small (as the aerial may be a rod only a few inches in length) that it is a parabolic mirror focusing the energy into a beam. Even longer-wave transmissions can be similarly beamed, using reflectors made of wire-mesh or similar light-weight material. If it is not practical to use such reflectors and directors we can use a number of aerials, suitably placed and phased to concentrate energy in one direction. But for the moment we can imagine the aerial itself to be, say, a vertical rod cut to an exact fraction of the wavelength used, and therefore resonating most readily at the desired frequency; a rod equal in length to half of the wavelength is commonly used. This rod will propagate waves in all directions, but if we stand a series of somewhat similar rods

at proper intervals in one direction we shall make them resonate too, and we shall thus get a strong transmission in this particular direction. Equally we can stand similar rods at distances which are chosen where they will hinder rather than help the propagation, and this, of course, makes the system still more directional. The whole array thus takes on the appearance of a giant tooth-comb, but the mathematics of it are unfortunately not so obvious as its appearance.

When we have arrived at a highly directional system, making our beam as much like a pencil of rays as possible, we must have some method of moving the beam to scan all space where our object may be located. We can do this in one of three ways. We can move the whole aerial and reflector. We can keep the big reflector fixed and move the aerial itself; obviously this becomes difficult at extreme ends of the traverse, where we shall need to have the reflector specially shaped to produce a constant field strength over the entire field of coverage. Third, we can keep both aerial and reflector fixed, and obtain the necessary beam-shift by electrical means. This method is useful where one needs to scan only a small sector, and techniques have been worked out for electrical scanning by such methods as phase-shifting. The alternation of effective angle of the beam is small, but the scheme is useful where for operational reasons we must have a very rapid rate of scan, and it would be physically impossible to rotate or vibrate the aerial array itself at such a speed.

The next link in our chain is the aerial feeder. Much similarity will be found about aerials both at transmitting and receiving ends, and, indeed, we shall discover that quite a number of radar systems use the same aerial for transmission and reception. As the giant pulse is transmitted a rapid electrical switch comes into

operation and switches off the receiver, lest it be saturated by the outgoing transmission. But, instantaneously, the transmitter is then cut off, and for a comparatively greater period of time the aerial is then connected to the receiver, so that the returning echo may be picked up. Then comes the next transmitted pulse, then a listening period again, and so on, hundreds of times a second. A small complication is introduced by the presence of the aerial switch, but in high-frequency radar technique we have found several comparatively simple ways of effecting such a rapid switching, and there is, of course, much saving in space and weight by using a joint aerial for transmission and reception (or 'common T and R,' as the system is generally termed), as well as greater accuracy in display, because no discrepancy can arise such as might be the case if we had a separate aerial for T and R and they failed to move exactly in step while scanning the skies.

But, whether separate or common T and R aerial arrays, we must link the system with the transmitter and receiver. In ships and aircraft it is obviously very difficult to have high-voltage power units, complicated modulators, and high-frequency apparatus anywhere near the aerial. Seaborne radar may have to be several hundred feet away from its aerials, and the pulse system and high frequencies used are such that a single linking-wire, such as the 'lead-in' of a broadcast receiver from its aerial, is quite impracticable. To carry the radio-frequency energy from the radar transmitter to the aerial, and the echo back from the aerial to the receiver, we must have feeders, or transmission lines, as they are sometimes called, carefully balanced to the circuits they link. This system of feeders is similar in theory to the transmission-line theory used for commercial and broadcast transmitters. Now that radar employs very high

frequencies the normal transmission-line links are not very efficient or practical, and it has been found possible literally to 'pipe' the transmitter and receiver to the aerial! These midget wavelengths appear to travel almost without loss through pipes or conduits of suitable shapes and dimensions, and the conduits, which we call 'wave-guides,' are all part of the ordinary radar very-high-frequency technique.

Now we come to the final link in our chain—the magic eye with which we hope to display our received echo, and gain operational information from its position. On an early form of radar known as 'Monica,' used during the War to warn bomber crews that enemy fighters were approaching from behind, there was no visual display, but the radar set on detecting fighters in its zone caused a series of high-pitched pips to be injected into the aerial 'intercom' system. The information given in this way was subsequently found to be insufficient for operational needs, and a visual display was given on a cathode-ray tube. The system is mentioned here, however, as being one of the very few instances of a radar system which did not use a CRT for display. For the great majority of systems the CRT is the 'eye,' and is the equivalent of the loud-speaker in the normal broadcast-receiver chain. Whereas the loud-speaker is called upon to handle a range of low frequencies and harmonics, all between about 50 and 10,000 cycles per second, the displays on the CRT screen are varied and complex. The CRT and its application to radar is thus a complete story in itself.

IV. ON THE SCREEN

WE SHALL FIND ALL MANNER OF ANACHRONISMS IN radar, and one of the most curious certainly applies to the CRT, which we now know stands for cathode-ray tube. The tube was given its name in the very early days of electron research, certainly before radar was dreamed possible, and when all manner of rays were being discovered and tested. 'X-rays,' 'gamma rays,' and 'anode rays' were the labels given to emanations from various forms of tubes, and the name 'cathode ray' was then appropriately given to the type of valve in which 'rays' from the heated cathode were caused to display their presence on a fluorescent screen. But obviously what we are displaying are not 'rays' in the normal sense, but fluorescence set up by electrons shot off from a heated cathode; and therefore it is just as correct to describe an ordinary radio valve and quite a number of similar devices as 'CRT.' They are all tubes which utilize the flow of electrons from a heated cathode.

Anyone who has seen a CRT in an oscilloscope or a television set will be familiar with the large pear- or bottle-shaped bulb. Tubes used in radar range from about four inches in diameter to those with a tube-width of over a foot. Types of fluorescent screen vary in colour, sensitivity, and other factors according to the radar display needed, and the electrode construction of the tubes varies according to the deflection of the electron beam needed to produce a requisite display.

There are basically two types of CRT—the 'soft' or gas-filled and the 'hard' or highly evacuated. Radar uses the hard tube.

At the foot of the tube is the cathode or filament, glowing and releasing electrons, negative electrical charges, just as does the filament of a radio valve. These released electrons can be attracted if a neighbouring plate or cylinder is given a positive charge, or they can be repelled back into the cathode if the plate is given a stronger negative charge. Alternatively the cylinder may be placed end-on to the cathode and given such a strong positive potential that the electrons released from the cathode form a beam and are attracted away at such a high velocity that they do not stop at the positively charged cylinder, but continue on. In a valve it is customary to place the greatest positive potential on the plate, or anode—say, 150 or 100 volts, compared with only 100 or 120 on any intermediary grid—and the anode is relatively close to the cathode, so there is a heavier electron-flow, or, as we say, a greater flow of anode current. By this we really mean a greater flow of electrons to the anode.

In the CRT we use a considerably greater voltage on the electrodes corresponding to the valve anode, often as much as 3000 volts. This anode construction is placed relatively much farther away from the cathode, and the effective anode current is often only a few microamperes (millionths of an ampere). But the electrons are drawn away from the cathode so fast that they pass almost right through the anode construction, and travel on to the far end of the tube, hitting the screen end of the glass at a velocity usually in the nature of 15,000 miles a second. The anode construction, as we shall see, is so arranged that the electrons are drawn off the cathode and focused into a fine pencil. So when we deflect the CRT beam to produce a radar display, what we are really doing is shifting a continuously moving stream of electrons, which are themselves moving at a speed of

15,000 miles a second. In a radar tube of the average diameter it is not at all uncommon for the display picture to be traced out by this curious moving finger at a writing speed of several miles a second. We do not *see* the beam, of course: what we see is the fluorescent effect of the sharply focused electrons impinging on the surface.

While we are, so to speak, at the screen end of the tube let us just see of what it is composed. Radar patterns are in blue, green, or similar colours; our needs are rather different from those of television, where we require as white a picture as possible. The colour depends on the chemical nature of the screen, and zinc silicate (Willemite) is a commonly used material, giving a bright-green spot. The chemical fluoresces when the electron beam touches it, and, of course, there is no connexion between the natural colour of the powder applied to the end of the tube and the colour it exhibits when under fluorescence; most of the screens are whitish in colour, viewed in natural light, but they fluoresce only according to the chemical structure. The electron beam 'lights up' the substance, and not unnaturally this fluorescence takes some time to die away; there is a natural tendency for it to continue glowing for a minute period of time after the electron pencil has moved on. This we call the afterglow, and although it can be a nuisance in television, it provides the answer to many operational problems of radar.

Cadmium and calcium tungstate have a very short afterglow—in fact, the spot dies within about 7 microseconds (seven-millionths of a second) after fluorescence. Zinc silicate has an afterglow of about 8 milliseconds (eight-thousandths of a second); while right at the other end of the scale is the 'red screen,' composed of zinc phosphate, which gives a glow lasting for nearly

a quarter of a second. The degree of brilliance is important, for with modern tubes we can focus the electron beam right down to a small circle about $\frac{1}{4}$ mm. in diameter, so that there is not a very large area to cause fluorescence on any one part of the tube.

There is no need here to go deeply into the operational uses of afterglow, but we can easily see that a steady radar pattern—say, one resulting from a blip of a steady response—will paint a nice, clearly defined picture on the tube, whereas spasmodic, sudden bursts, such as those caused by interference or unstable, spurious echoes, will be fainter in comparison. The long, steady echo has afterglow to help it, but the sudden, short burst does not produce the same brilliance of afterglow. On the other hand, a long-afterglow tube would tend to paint a heavy picture from all responses, desired and undesired, and after a fraction of a second the whole tube surface might be quite blurred and unreadable. In war, where an operator has to cope with enemy interference, it is often necessary to have tubes of blue and green, giving short and longer afterglows respectively, each being read as required through an optical colour filter. The same technique can be employed in peacetime navigation to cut down, optically, trouble from receiver noise, outside spasmodic interference, and similar snags which cannot be separated electrically.

But before we can produce our fluorescent picture we must achieve two things: we must first focus our electron stream into a beam; then we must find ready means of deflecting it to make the desired picture.

Disposition of the electrodes in the CRT is really a problem in electron optics, a new branch of physics requiring a volume for adequate treatment, but it will be appreciated that if the electron stream is being 'pulled away' from the cathode through a cylinder about

eight inches away, and charged positively at some 3000 volts, then a similar small ring or cylinder only an inch away from the cathode, and given a small negative charge, not only will tend to keep the stream back to the cathode (and so retard its outward velocity), but will also repel the stream at the point of the ring, and so narrow the beam's diameter. Similarly, more than one positively charged anode may be used, so that the electron (negatively charged) beam has to pass through several cylinders or apertures in discs on its outward route. These voltages, applied to each stage of electrode, can be so adjusted that there is a varying electric field, and at each point the beam can be deflected just as rays of light would be deflected by an optical lens. The shield near the cathode is usually known as the grid, and because of its geometric position has the same controlling effect on the electron beam as has the mesh grid of an ordinary radio valve. In radar circuits this grid may be a multiple electrode, or may be used for a variety of purposes. For instance, we might wish to have a fine control of voltage here, putting an instantly variable negative charge on the grid as a 'brightness' control for the tube picture. The more we make the charge negative the more the beam is repelled, and, as it were, throttled down.

Or we could keep a steady small negative charge here to throttle down the beam, but link the grid circuit to the signal circuits so that a momentary voltage which is caused to deflect the beam also, instantaneously, causes a minute decrease of the negative grid voltage. The effect of this is to make the beam stronger at the precise instant that it is deflected. This is just what we want for the strobe effect, which, as we saw, was the brightening of the spot at one point of the pencil travel; in most radar circuits the strobe effect, which is puzzling for a

beginner to fathom, is, indeed, quite simply produced just by control of grid voltage.

In a radio set the valve anodes are usually a hundred or so volts positive, and this is a positive voltage above earth, for the metal chassis of the set is negative and usually earthed. Thus if the valve-caps are touched a shock is experienced, because the fingers are being placed on a point, say, 150 volts above earth. But it would equally be possible to earth the valve anodes. Then the body would experience no shock on touching them, but all other negative parts would produce a sensation of shock, because they would be 150 volts 'below earth,' as we say in radar parlance. A layman usually thinks of the risk of getting a shock off only a 'positive' voltage, but, as the body is usually at earth potential, with the feet standing on the ground, what really matters is the voltage with respect to earth. Now in radar the operator is looking at the end of the tube, and if there is any danger of his touching part of the apparatus it is the tube end. That, as we can see, may quite often have a voltage of some 3000 applied to it, enough to cause a fatal accident. In many radar outfits, therefore, the actual screen end of the tube is brought to earth potential, and the high-voltage anode in the tube is earthed. The cathode is thus 3000 volts below earth, and the grid and inferior anodes are also probably a thousand or more volts below earth; a shock is experienced if they are touched, but the high-voltage anode end is safe. Of course, a surface charge tends to accumulate on the inside of the tube itself, owing to the electron beam impinging on the glass wall. If no means were provided for draining away this surface charge the electron beam of the CRT would continuously be 'going nowhere very fast,' and a saturation charge would build up. This we prevent by making the end and walls of

the tube slightly conducting; a thin deposit of graphite is the usual solution to surface accumulation.

Lateral attraction or repulsion caused by voltages applied to the tubes, slotted discs, and other electrode shapes inside the CRT cause the beam to be speeded up, thinned down, and generally brought as nearly as possible like a pencil, so that it may impinge on the screen end and cause fluorescence over an area probably not more than a ¼ mm. square. Our electron pencil is ready to write. For radar displays we must now find means of moving it in at least two directions.

The beam is one composed of electrons, travelling at high speed. They can be shifted from their path by electrostatic or electromagnetic means. If we so shape our focusing electrodes the shift of the beam from its non-deflected position can be achieved without any serious effect on the focusing. Electromagnetic deflection we secure, of course, by placing a magnetic coil or series of coils near the tube, and usually so arranged that the greatest concentration of the magnetic field is at that point where the beam has passed by at least one focusing anode. Electrostatic deflection we achieve by having pairs of facing plates inside the tube (placed usually after the final focusing electrode), the plates having their major electric field at right angles to the deflected beam. To avoid confusion it should be remembered at this stage that horizontally placed plates will deflect the beam vertically, and vertical plates will deflect it horizontally, according to the charge on the plates. In many radar systems we use both electrostatic and magnetic deflection at once, and simultaneously we control or modulate the beam by a varying voltage on the tube grid. The electrons striving to go on their unchecked path at 15,000 miles a second are thus given quite a task! Magnetic tubes usually have a rather long

'neck' in which all the electrodes are placed, leaving still a circular space around which the magnetic poles can be placed. Electrostatic tubes usually have two pairs of plates, the vertical pair (which, remember, pull or push the beam along a horizontal plane) being known as the 'X' plates, and the others the 'Y' plates. These terms arise, of course, from the familiar X and Y axes of a graph.

In a magnetic tube the sensitivity depends almost entirely on the physical construction of the magnets, but in an electrostatic tube there is quite a lot we can do, in addition to securing a maximum change of voltage on the plates to deflect the beam, to increase sensitivity. If we can afford to limit the possible amplitude—*i.e.*, the amount by which we need to deflect the beam to produce a reasonable radar display on the screen—then the plates may be placed quite close together to increase the potential gradient between them. That they cannot be too close is obvious, for in an extreme case the beam would touch one edge of the plates at maximum deflection.

We can regulate sensitivity by another means. The control of anode voltage affects sensitivity—in fact, sensitivity and voltage on the final anode are almost in direct proportion. A rough-and-ready method of appreciating this point is to visualize that as the anode voltage is raised the electrons are pulled 'harder' from the cathode; the beam is thus more intense and more difficult to deflect from its normal path. In truth the velocity is not so increased, but nevertheless with electrostatic deflection there is an almost linear relationship between anode volts and tube sensitivity. With magnetic tubes the sensitivity does not depend so directly on the voltage, being with most radar tubes of normal construction inversely proportional to the square root of the voltage.

For the basic radar display we have so far considered it will be recalled that we are faced with a time-base display in which the spot moves horizontally—that is, between the 'X' plates—taking a time to do so which bears relationship to the velocity of the electromagnetic wave-speed of 186,240 miles a second. Then we apply our radar-received signal to the 'Y' plates, which can produce a vertical deflection of the spot, making an echo 'blip' when a signal is received, or when the transmitter pulse goes forth. This display, known in radar spheres as 'Type A,' or 'range amplitude,' is historically the oldest, still much used operationally, and the easiest to consider as our basis.

At once you will see an important difference between the jobs the X and the Y plates are expected to do. The X plates are being fed with a regularly varying voltage, produced by a local piece of apparatus known as the time-base, to pull the spot across the tube, to black out its return path, and then to set it going across again in exactly the same path. This is a 'home-made' voltage, and we can make it as strong as we like within reason. But across the Y plates we have to place our signal voltage, which even with most efficient radar amplifiers may still be very small compared with the time-base voltage on the X plates. Thus the sensitivity of the tube in the Y direction needs to be considerably higher than in the X direction. This involves important constructional considerations inside the tube, and the Y plates may be placed much closer together than the X plates. Alternatively we can use, say, electrostatic deflection in the Y direction, and magnetic deflection in the X direction to produce the regular beat of the time-base display.

Where we have two pairs of electrostatic plates it is common in a badly adjusted tube to find evidence of

'trapezium distortion,' a name arising from the trapezium-shaped figure which can, in extreme cases, result from this distortion. The cause of the trouble is the influence of one pair of plates on the sensitivity of the others. If voltages are applied in turn to the X and Y plates which should pull the spot over the screen area in the form of a true square, then the effect of trapezium distortion is to produce a trapezium-sided figure, the difference between the long and short sides of the figure being an indication of the variation of sensitivity in one direction with the deflection voltage applied to the opposite pair of plates. Asymmetrical operation without some distortion is rather difficult to achieve, but is almost entirely cured by correct disposition of the X and Y plates and adjustment of voltage.

In tube displays so far we have considered only that type wherein a coated surface is caused to fluoresce on impact of the electron stream, and the radar operator sees this pattern on the tube end itself. But we must also note the extremely important new technique opened by tubes of the Skiatron type, where the picture is not watched on the tube end, but is projected optically on to a large screen. The fluorescent screen used on Skiatron-type tubes does not show much apparent change to the human eye when the electron beam traces out its pattern, but the chemical structure does, in fact, change in opacity under the impact of the beam. A beam of light is passed through the tube end, and projected by relatively simple optical means on to a ground-glass screen. The radar display drawn out by the electron pencil is thus enlarged up to the size of the screen.

In practice the translucent screen can be several feet in diameter, and the 'picture' is projected through a lens-and-condenser system. The tube screen turns a darkish purple under the impact of the electron beam,

and returns to its normal greyish colour when the beam has moved on and it is subject again only to the heat of the associated high-density light source.

We should by now be able to understand the basic points of the range-amplitude radar display. We see a faint greenish or blue line (depending on the afterglow-factor type of tube employed), with perhaps a large blip at one end of the line representing the transmitter pulse, surrounded by a group of PE's, the permanent echoes from neighbouring objects; or the outfit may more likely be of the type where the pulse and perhaps the PE's too are suppressed. As the gain control of the radar receiver is turned up we see the thin time-base line increase in thickness and take the appearance of a grass carpet, as the noise background of the receiver causes thousands of little impulses across the Y plates. Range control is then set so that the electron beam is travelling at a speed bearing relation to the required range of the outfit. The Cal is switched on, injecting on to the Y plates, instead of a radio signal, a locally generated series of direct-current pulses separated by a predetermined time interval, such as $\frac{1}{9312}$ second, which corresponds to increments of range equal to ten miles. These '10-mile pips' we spread out by means of another voltage control until the required time-base length is available. Our electron tape-measure is now ready for action. Cal is switched off, and the radar receiver instead put direct on to the Y plates. If any ship or aircraft is within our range, and within the direction of our aerials, we shall see the homecoming echo displayed as a small blip, or deflection, somewhere along the time-base line. There may be not one but a large number of echoes. Some, even remote ones, may be PE's; some will be moving in towards the end of the trace; others will be moving out. If we have set the tube up accurately according to

our Cal pips we can measure directly along the line, and say at once that any particular echo is from a target so many miles, perhaps over 250 miles, away.

When a target in which we are especially interested comes quite close to our station (provided the transmitter and receiver are functioning well, and the target is still being received back at good strength) we may find it convenient to use a different time-base for more accurate measurement. We therefore switch on a 'faster' time-base, corresponding to a smaller range, but giving us, as it were, a more magnified picture of the near-by echo in relation to our home station. Some radar outfits have a choice of several time-bases, the 'fast' ones giving an open and more accurate reading for near-by echoes. On the other hand, the maximum range is limited mainly by two things: first, there is the physical limit at which the apparatus will give any sensible reception of an echo from a very distant object; second, there is the limiting factor set up by the spacing between the pulses, or, as we prefer to regard it, the PRF. If we do not allow a sufficient space of time between pulses for an echo to be received back from the most distant range at which the outfit will work we shall get a false set of readings. Homecoming echoes will, in effect, be drowned by fresh pulses going out. There is, therefore, a certain relationship between PRF and range, just as a man who wants to get a nice, loud echo back from shouting at a mountain-side makes a clear pause between each shout, and does not jabber while the echo is returning. But this is a point more to be considered by radar designers than users.

A CRT is the radar eye, to the onlooker; but, of course, the real 'eye' of radar is the aerial system. It is the aerial which is all the time 'looking' out into space and finding our echoes for us. If we make our aerial

directional, then we shall not be confused by trying to look in all directions at once. But the more directional the aerial becomes the more limited is the field over which it can see. That field can be drawn out quite accurately in the form of what is known as a polar diagram; polar diagrams usually take the shape of a number of balloon-shaped lobes, and these are really only graphical representations of the limits of area over which the aerial can transmit or look. Now we shall discover when we look at some operational points of radar that the simple range-amplitude, or Type A, display gives us some idea of where our target is, but not how high it is. If we are working marine radar we do not expect to find the *Queen Mary* sailing 3000 feet up, but with radar for military or civil aviation the matter of height-finding is very important. In fact, for some radar uses, such as those where the magic eye of radar brings great aircraft safely in to land in dense ground fog, accurate height-finding is the *only* thing that matters. The pilot can tell by quite a number of other means where he is over the airfield; all he needs to know for a safe landing is how high he is at any moment.

Height and the more ready appreciation of a number of other operational points compel us to use in practice more complex radar tube pictures than the simple Type A, but if we have grasped the idea well so far we need not hesitate to consider some of the more advanced displays.

V. RADAR TIME-BASES

EVERY RADAR DEVICE WHICH DEPENDS ON TIME measurement must have a means of pulling the CRT spot along a display path at a certain speed, so that deflection from this path resulting from received signals or other pulses can be read with relation to some fixed standard.

The apparatus which moves the spot in this way is known as the time-base, or more accurately as a time-base generator. It is really only an electronic method of measuring time, and is a series of circuits that produce a potential which varies at a known (and usually constant and linear) rate with respect to time. Time-base generators are to-day an elementary part of electronics, and in this chapter we need only describe the general types and see how they can be applied to radar uses. Many time-base generators which are valuable in general industrial and laboratory work are useless for radar. Although time-base generators for television sets are relatively complicated—and, indeed, two time-bases are needed, as the tube is scanned horizontally 405 times while traversing the tube screen twice in a vertical direction—they are not suitable for the majority of radar systems, as the degree of linearity may not be sufficient. It will readily be seen that if we do need a radar display where our electronic clock demands a linear time-base, then there must not be the slightest variation in the potential's straight-line characteristic, or we shall have the same trouble in getting correct timing (and therefore correct reading of distance) from our radar clock as we should from an ordinary clock the hands of which did

not maintain an exactly constant speed in travelling from midnight to midday.

There are two basic forms of time-base generator, those using hard (highly evacuated) valves, and those in which the potential changes result from a discharge taking place through a gas-filled (soft) low-resistance valve. For most radar time-bases it is generally desirable to obtain what is called a linear saw-tooth voltage wave-form—that is, a voltage which increases uniformly with time for a certain period, and is then restored to its starting value in a very much shorter period, and can graphically be shown by a figure such as , so that, of course, the perfect form would be shaped thus: . With many radar time-base circuits we do, in fact, get such a close approximation to an instant flyback that the graphical representation is, indeed, very close to this latter figure.

This saw-tooth voltage is applied to the CRT in such a way that the spot is swept across at a known speed from left to right (usually) in a Type A display, or from the centre of the tube to the outer diameter in the case of a rotating PPI display. And at each end of such a journey the spot is sent very rapidly back to its starting-point, the flyback usually taking only a negligible interval of time, so that the path is only faintly visible on the screen, or, indeed, may not be seen at all by the human eye.

The basic principle of many radar time-bases is the charging of a condenser at a uniform rate, and then its discharge at the appropriate instant through a low-resistance path.

A condenser connected to a fixed-voltage supply charges at first with a rush, the rate tailing off as the

condenser voltage begins to approach the supply voltage. Theoretically, of course, the condenser never does attain the full voltage of the supply, but, apart from this hairsplitting point, the essential is that the current drops to zero at full charge, so that the graph of voltage against time is of the form , and the graph of *current* against time is the converse, .

We could attempt to straighten up the voltage-time curve if, instead of linking the condenser to a constant-voltage source, we made arrangements to maintain a constant rate of flow of current into the condenser. For this purpose you must imagine a variable resistance in series with the condenser. We are measuring the voltage across the condenser only, of course, and not across the resistance. At the moment that the condenser is first connected we turn the resistance up to maximum, decreasing it as the condenser becomes gradually charged. We should, if such a feat were humanly possible with components of normal radar values, then get a fairly straight-line graph of voltage against current. It would, in fact, be , and not .

Naturally no human co-ordination of hand and eye could achieve such a result of controlling the series resistance to limit the voltage in this way, but we can get an approximation of the plan by charging the condenser through the effective anode resistance of a pentode, or through a saturated diode.

Except at very low values, the anode current of a pentode is almost independent of its anode voltage—a characteristic of such valves brought about largely by the mechanical construction and geometric placing of the electrodes, and one which is most useful for radar.

In some time-base circuits we can put the condenser to be charged in series with an ordinary rectifying diode, and we get almost the same effect because there is a limited electron cathode emission, and after a small initial anode-current rise it cannot grow again even though the voltage is increased.

Thus we have solved the first essential of our time-base, to get a straight-line charging rate, which means, of course, a straight-line graph for the CRT figure. If we do not mind using a very high charging voltage, then, of course, we need not be unduly troubled by the curved nature of the first voltage-time curve we have examined. Although its overall shape is thus , we can produce such a curve by a relatively high voltage, and then for our time-base portion work on only a very small part of this exponential characteristic, and the smaller the part from which we work the nearer will be its approximation to linearity. There are several time-bases which do, in fact, have their condensers charged direct through a resistance, but the high voltage is an obvious disadvantage. Moreover, even on a very small part of this curve we do not get so near to linearity as we do with the flat part of the anode-voltage and anode-current characteristic of a screened pentode.

For the discharge we may arrange that the condenser value of voltage is suddenly reduced by automatic discharge through a gas-filled triode such as a thyratron, and we can set the circuit values so that the condenser will continuously be charged and discharged, producing a succession of saw-tooth wave-forms. Or we can arrange the circuit values so that after initial charge the condenser does not become discharged until another small voltage change takes place, and this voltage change can come from another circuit, so that the time-base display

on the CRT depends *each time* on this additional triggering circuit.

For lower frequencies the discharge through a thyratron is satisfactory. These valves are similar in electrode construction to a hard triode, but they contain a minute quantity of some inert gas. Immediately this gas ionizes the anode current rises to an extremely high value. There are small gas-filled thyratrons which have a cathode rating of only 5 watts, yet on ionization they are capable of passing 1 *ampere* of anode current. The point at which ionization occurs is determined, not unnaturally, by combination of grid bias and anode voltage. The initial anode current is very small usually, but immediately the grid bias is reduced beyond a predetermined point, or the anode current is sufficiently increased, ionization occurs and the anode-current curve rises sharply.

In the normal thyratron-type time-base generally the grid bias remains fixed, and the anode voltage is controlled by the voltage across the condenser. Immediately this reaches a predetermined value ionization occurs, the thyratron 'strikes,' and the condenser discharges almost instantly through this low-resistance path. It is worth noting that in most circuits the condenser does not discharge to zero volts, but to about 20 volts, which is a value so low compared with the 'striking' voltage of the thyratron that the circuit does give a true saw-tooth effect. During the following charging period of the condenser the thyratron is virtually a non-conducting path, and does not affect the linear charging curve we have striven to obtain. Of course, it will at once be seen that we can set the thyratron's working anode voltage and normal grid bias at such values that the thyratron will not 'strike' unaided even at the point of maximum condenser voltage. But a

slight alteration of grid bias, such as can be given from the associated trigger circuit, will permit the ionization, and then the condenser rushes to discharge. If in that interval the trigger voltage is withdrawn from the grid the circuit remains quiescent again until, the condenser having charged once again, the discharged is 'pipped off.'

The difference graphically is that with continuous working we obtain a succession of saw-tooth forms, such as . The vertical portion  is dependent on the *discharging* characteristics of the thyratron. The sloping portion depends for its slope and degree of linearity on the condenser and voltage values, and, of course, on the anode voltage and anode current characteristic of the screened pentode used as a charging resistance. But with the trigger in operation the saw-tooth form we obtain is shown thus , or, in other words, a series of  spaced by a time interval of , which latter is controlled by the trigger circuit.

The thyratron type of circuit is normally not suitable for very high frequencies, and then we have to use time-base circuits employing hard valves all through. There are many such, and the radar enthusiast who wants to probe the construction of such circuits is recommended to O. S. Puckle's *Time Bases* or Sir Robert Watson-Watt's *Applications of the Cathode Ray Oscillograph in Radio Research.*

Typical of the hard-valve time-base generators is that used in the Cossor Model 339 double-beam oscillograph, and a detailed description will be given of this, as it is quite simple to follow and shows how the standard hard-

valve radar time-base circuit works. It uses three high-vacuum valves, and is stable over the wide frequency range of 5 to 250,000 cycles per second. This upper limit of frequency sweep is determined and limited, of course, by circuit capacities and the voltage sweep required, and not by any such irregular and unstable factors as the deionization-time of a gas in a thyratron. Erratic behaviour of thyratron-type circuits is to be expected above 15,000 cycles per second.

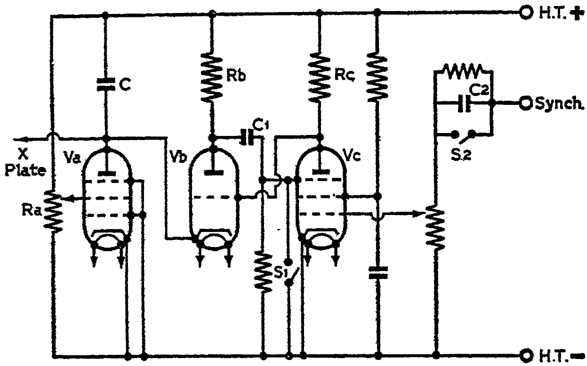


FIG. 1. A TYPICAL THREE-VALVE TIME-BASE GENERATING CIRCUIT

'Hard' (highly evacuated) valves are used throughout.

The circuit of the hard-valve time-base is shown in Fig. 1. The master-condenser is *C* in the anode circuit of valve *Va*. This condenser will, as we have seen, charge in linear fashion through the pentode, thus carrying the cathode of valve *Vb* more and more negative with respect to its anode. The control grid of this valve is, however, appreciably negative relative to the anode due to the voltage drop in *Rc* by the anode current of *Vc*. As soon as the cathode of *Vb* has travelled sufficiently negative to approach the potential present on the control grid of this valve, then *Vb* will start to pass current, and

at once a voltage drop will be present across *Rb*. This swings the suppressor grid of *Vc* negative, causing the anode of *Vc* (and therefore the control grid of valve *Vb*) to go positive.

This action is cumulative, and the master-condenser *C* therefore discharges rapidly through *Vb* until, when it becomes discharged, no further current flows through *Rb*. Then the cycle repeats. The value of *Rb* affects the amplitude of the triggering pulse present in the grid circuit of *Vc*, and also modifies the flyback period due to its presence in the discharging path, and this, of course, provides us with a trigger control. The voltage developed across condenser *C* before each successive discharge through *Vb* is dependent upon the extent by which the grid of *Vb* is maintained negative relative to the anode by the voltage drop across *Rc*. Adjustment of the magnitude of this latter resistance therefore gives us control of amplitude. Synchronization of the time-base with outside circuits is effected by injecting a fraction of the working voltage into one of the grids of *Vc*. The rate of charge of condenser *C* depends upon the capacity of this component and the current flowing through *Va*. In the Cossor oscillograph time-base advantage is taken of both these factors, rough control being effected by the selection of a number of fixed condensers on a rotary switch, while a progressive adjustment is provided in the form of a 'velocity' control varying the screen volts on the pentode charging valve.

This three-valve time-base circuit is typical of many used in radar practice, but there is one simple circuit giving a useful saw-tooth wave-form and employing only one valve. The circuit is shown in Fig. 2. This circuit is given, as it is typical of those in which the saw-tooth is produced from a *rapid* charge and a *slow*

discharge, or, graphically, , and not , as in the previous circuits described. This circuit acts on the principle of the 'squegging' oscillator, but it is important to note that the sweep frequency is not directly related to the frequency of the oscillations set up in the circuit,

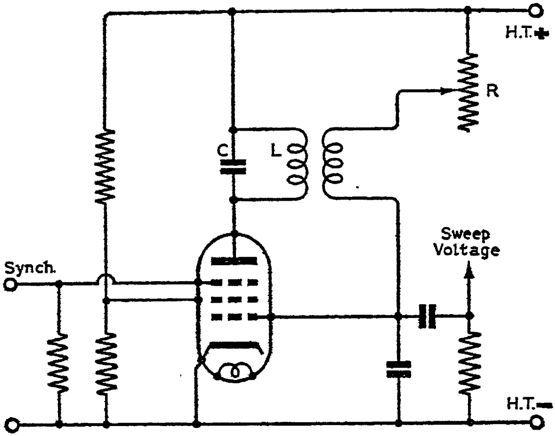


FIG. 2. A SINGLE-VALVE TIME-BASE GENERATOR, FUNCTIONING AS A SQUEGGING OSCILLATOR

which, of course, are principally controlled by the values of *L* and *C*. This latter oscillatory frequency must be higher than the sweep frequency to avoid interference. The circuit oscillates, and the grid of the valve rapidly becomes negative until oscillation is checked. The grid condenser then discharges through the leak *R* until the valve's grid voltage is once more sufficiently in the positive trend to allow oscillation to commence again. At once the grid voltage builds up negative, the grid condenser again discharges through the leak, and so the cycle continues.

Flyback suppression is sometimes added to a radar

time-base circuit to ensure that the trace is completely eliminated during flyback. This is generally achieved by applying back to the shield of one of the time-base valves a voltage of suitable phase taken from the sweep output part of the circuit. This voltage is generally applied through a diode rectifier, and, of course, the effect (if the voltage is in phase) is to 'wipe out' the spot during flyback.

VI. 'IMPOSSIBLE' CIRCUITS

A MAN WHO HAD SPENT SOME FIFTEEN YEARS IN THE construction and servicing of radio receivers was shown the circuit diagram of a 10-centimetre radar receiver used in a fairly popular civil-aviation beacon system. He studied the blueprint for some five minutes, and his quizzical expression clearly showed that he was on the defensive, thinking, no doubt, that he was being made the subject of a practical joke.

At length he said, "I don't know what it is meant to be. It couldn't work, of course. The circuit is quite impossible." On being told that no sport with his feelings was intended, and that the circuit was, in fact, an accurate delineation of a piece of commercial radar equipment, he remained puzzled and suspicious, and kept repeating, "But it couldn't work. The circuit is impossible."

Perhaps this is an extreme case, but nevertheless it is borne out by instructors who have to prepare radar mechanics and service engineers to handle civil and military radar. These instructors find that newcomers to the techniques of radio are prepared to take the admittedly strange radar circuits at their face-value, and will reason out for themselves the manner of the circuit's functioning. But the man who has become conservative, and who has hidebound ideas of radio theory, remains so puzzled by the comparative novelty of radar technique that he is at a great disadvantage. To him all valve cathodes are earthed. All grids stay at some negative potential, all anodes usually end up at 'high-tension positive,' and the whole purpose of the circuits in which

he has been trained is to handle 'nicely rounded' sine waves at the grid end and to deliver equally sine-looking waves, perhaps amplified or inverted, but nevertheless sine waves. The notion that a circuit should pass a square wave is revolutionary. That a string of some seven or eight valves may be needed to produce some peculiar little pulse (which the novice might imagine would be produced only too readily by a single stage of distorting LF amplification) is an annoying lack of apparent economy on the part of radar technique. But there it is; many of the circuits do appear revolutionary, impracticable, and to the conventional radio man 'impossible.'

In the scope of this book it is obviously not possible to deal with all radar circuits and manners of producing square waves, pulses, and bursts of energy in various time-forms. But if the reader has studied some reliable work, such as C. L. Boltz's *Basic Radio* or the Radio Society of Great Britain's *Amateur Radio Handbook* and its supplement, and is familiar with normal circuit theory and the use of the valve as a Class A, B, and C amplifier, then some of the most important radar circuits will not have a crossword-puzzle complexity.

The very names of typical radar circuits are often as intriguing as the operation: we have already met such strange additions to the English language as the 'strobe' and the 'Cal.' Now let us meet the 'cathode follower,' the 'D.C. restorer,' the 'flip-flop,' and the 'multi-vib.' We shall meet the 'transitron flip-flop' and several other circuits imported from American radar laboratories, but first we must be introduced to the two firm friends which run through all basic forms of radar pulse-shapers—the differentiator and the integrator.

We have seen enough of radar systems to realize that a 'short, sharp shout' is the fundamental of all transmis-

sion in this way, and therefore the major task of all modulator circuits at the transmitting end must be to create not a gentle sine wave to modulate the C.W., but as 'vertical' a square wave as possible to cause a *nearly* instantaneous burst of energy, and then a cut-off again as *nearly* instantaneously as possible. We need many circuits in the transmitter modulator, first to form a square pulse with a wave-form having a leading edge as nearly vertical as possible to produce a sudden burst of energy.

The nature of the circuit may also demand that the lagging edge be vertical, to produce an instantaneous cut-off. Such a wave-form is produced in the transmitter modulator, the pulse of energy is broadcast, and a signal received by the radar receiver. Now there is one important difference between a radar and a broadcast radio receiver. The latter continues to function all the time it is switched on, and, apart from the distortion introduced by 'detection,' the job of the receiver amplifier stages is to handle the sine-wave form and deliver at the loud-speaker a continuous output which should be as nearly as possible a mirror image of the microphone voltage wave-form at the transmitter. The process is continuous. Not so in the radar receiver.

Use of a common aerial for reception and transmission (a standard technique now in centimetric radar systems) involves some form of switch to insulate the receiver from the great surge of energy when the transmitter 'fires,' and to connect the receiver to the aerial in good time (although it may be only a minute fraction of time, perhaps a millionth of a second) for reception of the echo. The pulse is received, then amplified at radio frequency, probably by a superheterodyne arrangement which obeys conventionality in principle, even though the circuit and component values may be unorthodox

compared with broadcast practice. But for effective display on the CRT the pulse may not be 'square' enough. To produce a good vertical leading or lagging edge to the pulse, for accurate CRT reading, we may need to distort the received signal, to 'square it up,' and for this purpose we may put the signal through a 'pulse-shaper.' But an essential part of the receiver is not involved in the continuous chain of reception. We gain nothing by receiving the pulse and displaying it on a CRT unless we can relate the pulse in time to the time of the transmitted energy. In many forms of radar the *time relationship* between the transmitted burst and the received packet of energy, and the accurate measurement of this time relationship, is as important as the reception of the echo. Thus the time-base of the CRT is so arranged that the echo is presented not, as it were, on one continuous beam of fluorescence, but with each echo on a separate trace. The whole thing takes place dozens or hundreds or even thousands of times every second, so to the human eye it appears as a continuous process. But in the receiver itself the process is not continuous. In many of the circuits we must arrange not for steady voltage changes, such as those of speech frequency in a radio low-frequency amplifier, but for spasmodic, sudden, staccato changes. We need such bursts of energy, for instance, in saw-tooth form to provide the common form of linear time-base in basic radar equipment.

FIG. 3

To summarize, therefore, the average radio circuit is handling wave-forms which can roughly be represented as in Fig. 3. The radar receiver and transmitter, however, will be handling a square wave, such as is shawn

in Fig. 4, or one of its several variations, such as in Fig. 5.

FIG. 4

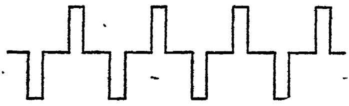


FIG. 5

How can such curious wave-forms be produced? The orthodox radio man will say at once, "Oh, these are merely distortions of a true wave-form. I am not familiar with a rectangular or 'square' wave, but obviously these pulses and blips are a distorted form of some truly geometric wave-form which has been applied to a distorter." That is true, but what is the cause of the meticulously arranged distortion? It is not, obviously, the result of circuit fault, nor an uncontrollable effect. We shall, in fact, discover on analysing many a radar pulse-shaping circuit that no matter how many valves are used the essential of the circuit is often the 'integrator' or the 'differentiator.'

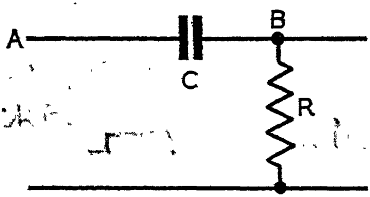


FIG. 6

First consider a simple circuit diagram (Fig. 6), consisting of a condenser *C* and a resistance *R*. This looks

simple enough, even to the hidebound radio man, but in radar this is a 'differentiating' circuit if the values are correctly chosen; so let us see what happens. If a sudden voltage is applied to point A point B will follow *at once* and rise by the same amount. If now the voltage at A is maintained steadily B's voltage will drop owing to the leak-back through R. Even a slow discharge will have an effect on the voltage at B, and we can, of course, control the rate of discharge by varying the values of the condenser and resistance. There is a fairly simple piece of arithmetic which can tell us the 'time factor' of such a circuit, for it can be shown that about two-thirds of the charge will leak away in a time equal to C multiplied by R, in seconds. If C is measured in microfarads and R in megohms, then the result CR gives us the time constant of the circuit in seconds or fractions of a second. We can make this time constant fit our radar needs.

FIG. 7

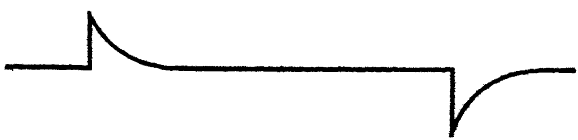


FIG. 8

Now look at the 'long' pulse (Fig. 7)—a sudden increase in voltage, maintained at a steady higher value for a certain time, then dropped almost instantaneously to zero. Let us say that the time interval is 50 microseconds, and that such a series of pulses be applied across the differentiating circuit just examined. The sudden

increase of voltage at *A* will last for 50 microseconds. If we arrange condenser *C* to be of 5 micro-microfarads and *R* 1 megohm the time factor is 5 microseconds. This means that by the time 5 microseconds have passed the voltage at *B* will have tailed off in a differential curve, so that at *B*, instead of the original square pulse, we get a series of pulses, as in Fig. 8. That is the result of putting a square wave-form through a differentiating circuit. Now a rather different effect is obtained if the circuit is arranged as in Fig. 9, the 'integrating' circuit. The time constant can be worked out as before, but it is obvious that if the square pulse be applied to point *A* the resulting wave-form at *B* will not be a series of rectangular pulses, but rather as in Fig. 10. This is the characteristic wave-form of the 'integrated' pulse.

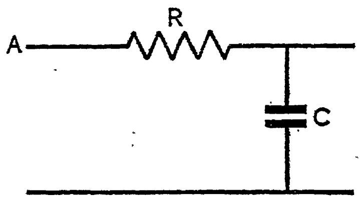


FIG. 9

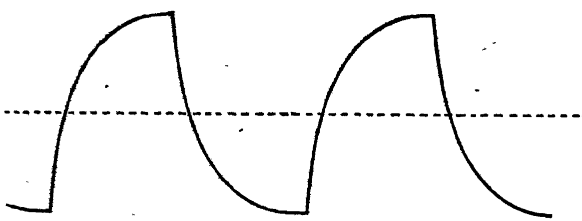
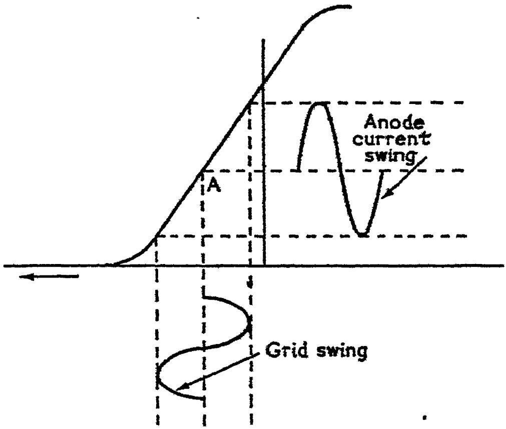


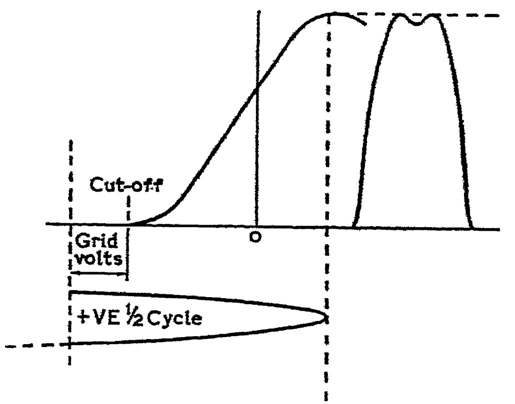
FIG. 10

How do we obtain our square wave in the first place? There are several methods, but one basic system is interesting because it takes a sine wave and turns it into

a square wave. If we consider an ordinary Class A valve amplifier, with a sine wave applied to its correctly biased grid, and the whole thing working on the straight part of the characteristic, then an amplified sine wave is produced in the anode circuit, a mirror of the grid input.



Class A



Class C

FIG. 11

Fig. 11 shows the type of operating conditions for Class A. But what happens if we shift the operating conditions to Class C, using the entire characteristic, biasing the grid to about *twice* cut-off? As the grid is driven positive, grid current flows, the anode current drops at the peak of the cycle, causing the top of the peak to be, not , as with Class A, or sometimes even Class B, but . What we get from such a circuit, if a large sine wave is applied to the grid, is a series of pulses such as . Obviously this is the first step towards a truly rectangular wave-form, and by applying such a series of pulses to a differentiating circuit we can get a series of saw-tooths, or 'pips.' A fascinating series of forms can be obtained, and I advise interested radar enthusiasts to read N. Marchand's "The Response of Electrical Networks of Non-sinusoidal Periodic Waves," in the I.R.E. Proceedings for 1941.

This method of creating pulses is used in many radar systems, but an even more popular circuit is that of the 'multi-vib,' or multi-vibrator, to give its full title, an honour seldom, I may say, accorded it by radar mechanics. The multi-vib is much older than radar. In fact, it was an invention of H. Abraham and E. Bloch at the end of the First World War, and in view of the secrecy which came to surround all producers of square waves (most especially the multi-vib) during World War No. 2, it is amusing to reflect that the enemy could have read it all for himself in Abraham and Bloch's *Notice sur les lampes-valves à 3-electrodes et leur applications* (Publication No. 27 of the French War Ministry in April 1918).

This particular ingenious application of the 'lampes-valves' makes use of two resistance-coupled valves, back

to back. A typical circuit is shown in Fig. 12. It will be seen that the anode of each valve is coupled to the grid of the other, of course through the usual grid condenser, with grid-leak to earth. To see how the multivib operates we must first 'catch' it at a quiescent state.

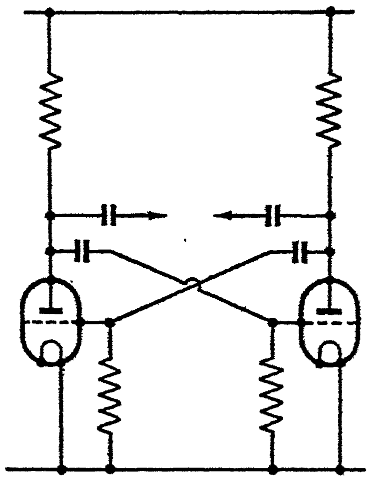


FIG. 12

At any such instant picture the anode current in one valve increasing. A negative voltage is thus applied to the grid of the next valve (because of the greater volts-drop across the anode resistance), and the effect of this negative grid voltage is to drive the steady anode current of the second valve down. This tends to make the grid of the first valve more positive, and still further increases the anode current of that valve. The effect is cumulative, and after a predetermined time the cumulative effect causes the anode current of one valve to reach maximum, while that of the other valve is cut off or reduced. Immediately the grid condenser's charge has leaked away through the resistance (here comes that old friend

the 'time constant' of an *RC* circuit again) anode current flows normally again in the second valve, and the cumulative effect starts building up again, of course, this time in the opposite direction. There is no necessity for the time constants of the two circuits to be matched. In many radar multi-vibs the two *RC* time constants are arranged to be different, or the valves are otherwise 'mis-matched' by the application of a small negative bias to one stage.

The multi-vib, you see, is really a resistance-capacity-coupled amplifier in which the output of the second valve goes back into the first. If you prefer a mathematical explanation, then I would quote the Admiralty Signal Establishment's stock 'arithmetical' explanation of the multi-vib, which incidentally applies equally well to the 'flip-flop' and 'transitron,' which we will consider next.

A positive voltage (say, 1 volt) is applied to *A's* grid. It produces a negative voltage at *A's* anode, which is fed to *B's* grid and produces a positive voltage at *B's* anode, which adds itself to the original 1-volt change. There will be two very different results, depending on whether the application of 1 volt positive will make *B's* anode go more or less than 1 volt positive.

Suppose that the effect of 1 volt positive is that *A's* anode goes $\frac{1}{2}$ volt negative, making *B's* grid, of course, also go $\frac{1}{2}$ volt negative. This will make *B's* anode go $\frac{1}{2}\times\frac{1}{2}$ (*i.e.*, $\frac{1}{4}$) volt positive. This extra $\frac{1}{4}$ volt at *B's* anode will cause a further change of $\frac{1}{4}\times\frac{1}{4}$ (*i.e.*, $\frac{1}{16}$) volt at *A's* grid, and so on. Mathematical proof exists that the resulting change can never exceed $1\frac{1}{3}$ volts, for this total is made up by continued addition of $1+\frac{1}{4}+\frac{1}{16}$, and so on, each term being one-quarter of the preceding one. Now what happens if the effect of 1 volt positive on *A's* grid is to produce an extra $\frac{9}{10}$ volt positive at

B's grid? The resulting change will be $1+\frac{9}{10}+\frac{81}{100}$, and so on, making a total which can never be in excess of 10. In these two cases, therefore, the effect of back-coupling is to increase the gain of *A* either by $1\frac{1}{3}$ times, or by 10 times. If the voltage on *A's* grid is removed the whole circuit goes back to its original state, and the circuit acts as a stable amplifier.

Now suppose that the effect of 1 volt positive on *A's* grid is that the extra voltage is 1·1 volts positive—*i.e.*, more than one. The preceding reasoning shows that *A's* grid will change in voltage by $1+1{\cdot}1+1{\cdot}21$, and so on, getting larger and larger until a limit is set only by considerations of H.T. voltage and valve characteristics. The circuit is unstable. The 'effect' is out of all proportion to the 'cause,' and, indeed, remains when the 'cause' is removed. This state of things occurs in all circuits of the 'flip-flop,' multi-vib, and Kipp-relay types. Nearly all circuits of this type begin (at some infinitesimal instant of time when the outfit is first switched on) as a *stable* arrangement. A minute voltage change, which rapidly builds up, puts them into an unstable condition. They 'flip' over into a stable condition, and remain in this state until (usually due to the charge or discharge of a grid condenser) they again became unstable and 'flop' back to the original stable condition. Sometimes the internal changes taking place after the 'flop' send them automatically—*i.e.*, with no external cause—into an unstable state again, and they continue 'flip-flopping' of their own accord. Such a circuit is the true multi-vibrator.

A similar explanation is given by the Admiralty Signal Establishment for that ingenious circuit the one-valve 'flip-flop,' called in America the transitron. It consists of a pentode with its suppressor and screen grid linked by a condenser. By suitable choice of component values

it can produce oscillation (when it is more usually known as a 'Numans oscillator'), and with different values it can be made to have a stable and an unstable state, the change from the stable to the unstable being produced by a positive-going pulse.

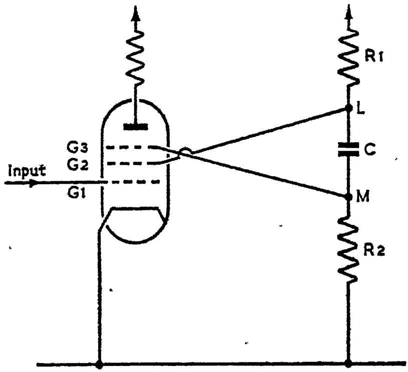


FIG. 13

In this circuit (Fig. 13) the connexions differ from the usual pentode arrangement in two respects. First, the suppressor grid *G*3 is connected to cathode (earth) through a resistance *R*2, instead of the usual direct connexion to cathode. The insertion of this resistance allows *G*3 to take up varying potentials depending on the other circuit conditions. The variation of the potential of *G*3 will in turn change the distribution of currents between the electrodes (particularly *G*2 and the anode). In general it will be found that if *G*3 is made a little negative the anode current will be reduced. If less current flows to the anode there will be more current available for *G*2. So more current flows to *G*2, which consequently becomes less positive, because of the increased voltage drop across *R*1. The second difference from the usual pentode arrangement is that a condenser

is connected between $G2$ and $G3$. This compels $G3$ to follow $G2$ in potential change as regards *instantaneous* potential changes.

Two separate cases are met with:

(*a*) If the drop in the potential in $G2$ which would be caused (in the absence of C) by the drop in the potential of $G3$ is less than the drop in potential of $G3$, the circuit will return to its original condition when the original 'cause' is removed. This is the *stable* state.

(*b*) If the drop in the voltage of $G2$ which would be caused by the drop in the potential of $G3$ is *greater* than the drop of potential of $G3$, the circuit will change violently to a completely different condition. This is the *unstable* state, which is used in the 'flip-flop.'

Case (*a*) corresponds to the condition of the multivib, in which, as we have seen, the extra voltage change on *A*'s grid is *less* than the original voltage change causing it. Case (*b*) corresponds to that in which the extra voltage change on *A*'s grid is greater than the original voltage change causing it.

Suppose that case (*b*) holds, and that a positive-going pulse is applied to the control grid $G1$, the potentials of the electrodes change and reach the following conditions of stability. $G3$ and $G2$ drop equally in voltage, $G3$ becoming very negative. The anode current is nearly cut off. The voltage difference between L and M (the condenser terminals) is the same as at the start. This state marks the occurrence of the 'flip' action.

The valve would remain in this new stable state if C had no tendency to discharge. In fact, C now starts discharging through $R2$ and the point M, and therefore the potentials of $G2$ and $G3$ will change slowly until a state similar to (*b*) is reached. At this instant the slow change in $G3$ and $G2$ voltages acts as a disturbance, and another violent change (the 'flop') takes place in the

opposite direction until the original stable state is reached.

Quite a number of radar circuits are coupled through a device known as a 'cathode-follower.' To see why this is necessary consider Fig. 14. This is the normal method of connecting a valve amplifier. The signal is applied to the grid, and a resistance (or inductive) load is in the anode circuit, so the ouptut is taken direct from the *anode.* The cathode follower (Fig. 15) has one important difference. The load is inserted in the cathode lead, and the output is taken from across this resistance. The gain is low, and the arrangement has little merit as an amplifier, but the output circuit can be made to have a low impedance, and is therefore suitable for connecting to a transmission line. It acts, in fact, as a transformer, with none of the difficulties attending the use of transformers for 'pulses,' such as the effects of internal capacity and resonances.

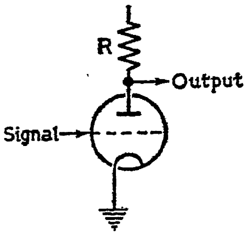


FIG. 14

This arrangement is known as a cathode-follower because the cathode follows the grid-voltage changes. If the resistor is made sufficiently large the cathode voltage will rise very nearly as much as the grid voltage. The normal cathode-follower has no resistance load in the anode circuit, but, of course, such an arrangement could be used, as in Fig. 16. The same current flows through both resistances. When a positive signal is applied to the grid the cathode rises in voltage; mean-

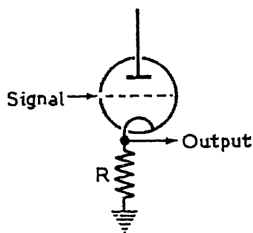


FIG. 15

while the anode goes negative—*i.e.*, the anode output is negative—and thus from the one cathode-follower it is possible to get a positive and a negative output simultaneously. This is often useful in coupling the last stage of a radar circuit to a CRT.

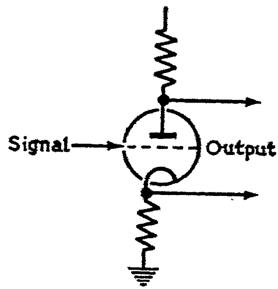


FIG. 16

'Gating' circuits are commonly used in radar equipment, and a typical circuit is shown in Fig. 17. The purpose of the 'gate' is to accept two sorts of pulses simultaneously, and to sort them out as required. For instance, the valve in Fig. 17 could have such a potential applied to the suppressor that the anode current would be entirely cut off. If we picture a string of pulses,

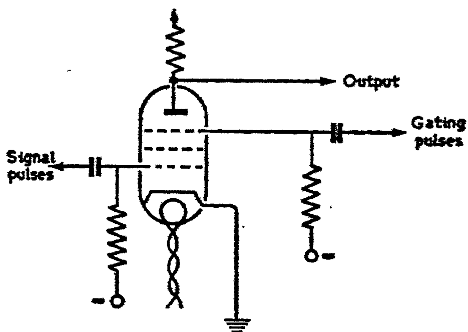


FIG. 17

such as in Fig. 18, applied to the control grid they will have no effect at the anode of the valve, for there is no anode current flow. But if the second set of pulses (Fig. 19), usually known as the 'gating' pulses, are

applied to the suppressor they may be arranged to be of sufficient potential at peak to permit an anode current flow for the duration of each gating pulse. Thus if the gating pulse coincides with the pulses on the control grid there is change in anode voltage, and the resulting output form is controlled at those instants only by both

FIG. 18

FIG. 19

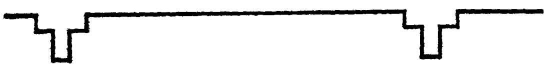


FIG. 20

sets of pulses. The final output may be of the form shown in Fig. 20, but, of course, there are many varieties of the 'gating' device. Such a circuit is used for the strobe. Signal pulses are applied to the control grid, and strobe pulses to the suppressor. The only output at the anode, if the valve is correctly biased, is that which coincides with the strobing.

There is no necessity here to describe the action of the D.C. restorer, for although this circuit is commonly used with radar CRT's, the D.C. restoration principle is well known in connexion with television and cathode-ray oscilloscope practice. The use of the diode for D.C. restoration is described in the *Amateur Radio Handbook*, in the section on television technique. But in concluding this brief survey of some unusual radar circuits which

the orthodox radio enthusiast would have found puzzling in view of their divergence from sine-wave practice, reference must be made to one very elegant way of producing square waves, by means of a delay line. A typical circuit is shown in Fig. 21.

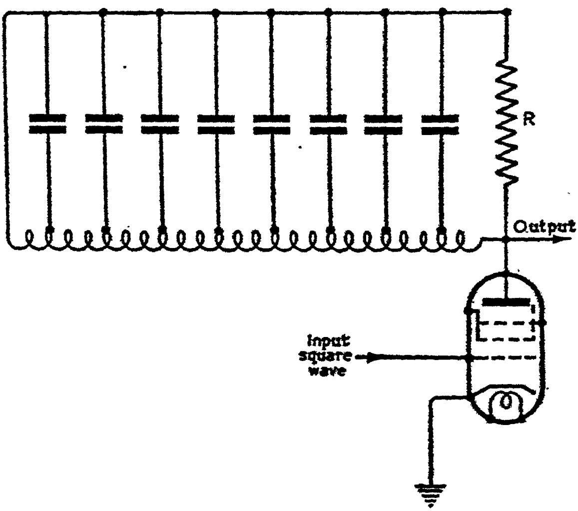


FIG. 21

The arrangement is fully described in O. S. Puckle's *Time Bases*, and the delay-line system is used when it is required to produce a series of pulses spaced by definite intervals. In the delay line the number of sections is arranged to be equal to 1·28 times the total delay required, divided by the time of rise of the pulse wave-front. The time required for the burst of energy to return to the input end of the line is dependent upon the electrical length of the line. When the pulse is reflected it is simultaneously reversed in polarity, so the resultant wave-form at the input end consists of a number of square waves, each of a duration twice the

time taken for the pulse of energy to travel from the input end of the line to the short-circuited end. Another delay line may be used to provide a second series of square pulses, at time intervals delayed with respect to the first.

Quite a number of these important radar circuits were devised for other purposes long before radar came into being, and prior to 1930 they were only of academic interest. Now they have a direct practical application, despite the fact that the conventional radio man classifies them as 'impossible.'

VII. PICTURE ON THE TUBE

RANGE-AMPLITUDE, OR TYPE A, DISPLAY ON THE CRT of a radar receiver would be of very little use with many modern systems, as the information it gives is not sufficiently accurate, nor can it be deciphered sufficiently speedily. We have seen that the distance along the time-base where the echo blip displays itself is a true indication of distance of the target from the pulse transmitter. Thus we can read the range, but without some other means we do not know direction; also, if our target is an aircraft, we cannot read its height from the simple Type A display. Moreover, the range of the echoing object must be read with some degree of accuracy by taking a measurement on the trace from the leading edge of the transmitter pulse to the leading edge of the echo blip. If we had to read this distance in inches, centimetres, or any other fraction of a standard measure we should need some way of translating this distance into true range.

In one type of coast-watching radar we do not bother to estimate the physical distance between the blips shown on the tube, but we move a control which shifts a definite strobe spot along the trace until the spot coincides with the echo blip on which we are taking a reading. As this control is moved to regulate the position of the strobe another circuit is simultaneously put out of balance, and thus, entirely independently, can give us a reading. Devices of this kind are numerous, and are generally known as 'electrical range-markers.'

The next most common variation of the straight Type A display is the Split. This came into use during

the War, when coast-watching radar equipments were being developed to give warning of approaching enemy aircraft. An indication of height was obtained by measuring automatically the angle of the line of maximum reception of the echo. If we could measure this angle and ascertain the range we could, by fairly simple trigonometry, find the unknown quantity, the height. To ascertain the angle of elevation with simple ground equipment which is not highly directional we use two aerial systems with different polar diagrams, or perhaps with the same aerial shooting in two different directions. Thus we can get two rather different conditions of reception, and by means of a switching motor or some similar device synchronized with the PRF we can check these two different conditions alternatively. To get a quick visual check we arrange that one echo is displayed along a trace similar to that described for the standard Type A, and then for the second set of conditions a different trace is switched on, usually displaced by having one trace start its travel a little nearer the edge of the tube than the other.

Persistence of vision will thus give the effect of two echo blips side by side, one of which will usually be greater than the other. If we know our aerial polar diagrams comparison of the respective heights will show us in what area is the effective 'line of shoot.' Thus we can ascertain the angle of elevation with respect to ground-level, and so know the height of our aircraft.

Although a Split display gives the effect of two echoes side by side (or in some systems one echo reversed, so that it hangs beneath), we should never forget that it is only persistence of vision which makes this picture on the tube. What is actually happening is that at one instant a pulse is transmitted and an echo received back, and this sequence is displayed on a trace; then, the next

instant, another pulse is transmitted through a different aerial (or through the same aerial in a different position), and the display of the resulting echo along this different line of shoot is given by a trace and blip display on the CRT a little distance away from the first display. As these two displays are being made alternately, probably more than a hundred times a second, the effect is to show two echoes simultaneously.

A full explanation of the Split system and of its operational use in conjunction with known polar diagrams of aerials is necessarily wordy and complex. But if we are content to take the polar diagrams themselves as really a rather rough sketch of the area covered by the lines of shoot of the aerial the operational aspect is not too difficult; and the Split display on the CRT is, of course, quite simply achieved by arranging that one trace is produced with a slightly different value of voltage on the X plates, to shift the alternate display slightly to one side.

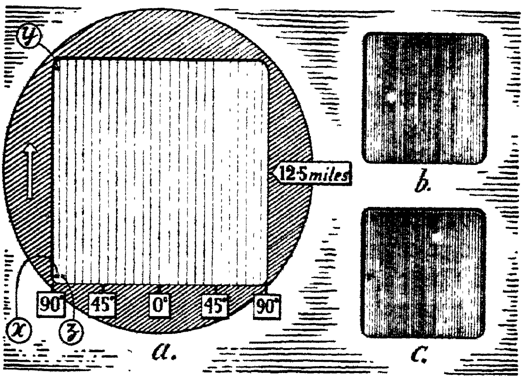
You can regard the Type A display as a very elementary, one-directional map of what is happening. On one side you have some indication of the transmitter pulse; then, a distance along the trace, you have the blip indicating reception of an echo. The distance between these two objects on the tube is proportional to the actual distance in space between them; but as a map it is too elementary to be of any other use than in indicating range, for we cannot tell which direction is being taken by the object giving a reflection. Of course, we could fit either our transmitter or our receiver with a directional aerial, and by rotation we should be able to get some idea of azimuth, just as one does in ordinary radio DF-ing. This system was, in fact, used in early coast-watching radar equipments. A type of directional aerial feeding into a goniometer was used to supply the

receiver. The gonio control was turned until maximum reception of the echo was achieved (readily shown by the period when the depth of the received blip was at its greatest), when, if the gonio control were suitably engraved in degrees corresponding to aerial-array positions in space, the true line of shoot could be determined. In many such systems the gonio was elementary, consisting of aerial arrays at right angles feeding into coils similarly placed in the gonio. The first stage of the radar receiver was fed from a pick-up coil which could be rotated by the gonio knob over the facing aerial coils. Accurate calibration of the gonio scale was arranged to coincide with actual aerial array position, but, of course, it will be seen that such an arrangement is equivalent only to the normal elementary 'frame aerial' DF, and gives indication of line of shoot only, without showing if it is to the back or front. This was not at first a disadvantage, for radar was visualized only as a warning system for detecting aircraft approaching from over the coast.

But when radar became miniaturized, and centimetric equipment was fitted to aircraft, some more easily decipherable map was essential than that given by the Type A. So the Type B, or range-azimuth, display was conceived. This gives a sort of distorted map of the area in front of the aircraft scanned by the radar aerial, and it is worth considering the system here, for it forms the basis of quite a number of aircraft radar systems.

The picture on the tube with Type B is, first, of a square of faint light. Somewhere in this square you may detect one or two brighter spots of light, indicating echoes received from aircraft ahead. This square is thus a graph, or a distorted map. The co-ordinates of the map are easy to appreciate. Horizontally is azimuth—say, 90 degrees either way of the central point. Vertically the radar 'graph' shows range up to, say, 25 miles. The

one essential difference between CRT's used in Types A and B is that B tubes use intensity modulation. In Type A the echo blip is 'pulled' up or down out of its horizontal trace by voltages applied to the Y plates. In Type B what we see is not a V-shaped blip, but a spot of light which is *brighter* than the lines drawn out for the rest of the trace, and this brightness is achieved by applying the signal not to X or Y plates, but, usually,



TYPE B DISPLAY

The spot moves upward from *x* to *y*, retraces and starts upward at *z* again, and so on. This is suggested in black lines in (*a*). (*b*) and (*c*) are specimen plots, the first showing a target 45° to the left of the line ahead and 12½ miles away, the second showing a target 30° to the right of the line ahead and 40 miles away.

Note. The pictures are merely illustrative, and are not to be considered accurate in detail.

to the grid of the CRT, so that the spot strobes itself and grows momentarily brighter as a signal is received.

The Type B square is drawn out by the trace in the following manner, which is rather interesting to follow. The tracing-spot starts its journey at the bottom left corner of the CRT, and is moved up to the top left corner, covering a distance equal to the maximum range of the radar equipment. It is then suppressed, travels

back to the bottom line, and starts a fresh painting of an upward line simultaneously with the next outgoing transmitted pulse. This line is not over the preceding one, but is displaced slightly to the right; indeed, the successive sweeps are spaced out over the square to correspond with the azimuthal direction in which the aerial is sweeping. If the aerial were checked in its mechanical sweep and set pointing straight ahead, then all we should see on the screen would be a single line formed by the spot moving up and down at the centre of the rectangle. This is in the 0-degrees azimuth position. Maximum displacement to left or right is (usually) 90 degrees, and if it were not for the slowness of human vision we should see the spot tracing out a faint pattern like the teeth of a comb, with the teeth at the left numbering from 90 degrees down to zero at the centre, then to 90 degrees starboard.

With this display we do not see the comb pattern clearly, because a screen is chosen which has a fairly considerable afterglow, leaving a greenish-grey (or blue-grey) faint square of light. On this background sudden spots of light appear as the tracing-spot at that very instant is strobed, indicating an echo. This display does not show height, of course, but if you regard the picture on the tube as a distorted sort of map of what is seen ahead of the aircraft you will realize that at once, without any mathematical interpretation, the pilot can see the azimuth of his object, and its approximate range. A fine graticule can be placed over the end of the CRT screen so that these essential figures can be read at once.

A kindred display is the Type C, where again the aerial is rocked mechanically, and the spot moved in step, so that a rough map is drawn. This time it is an elevation-azimuth display, and the form is what is known as helical scanning. It may not be vitally necessary for a

pilot to know the exact range of his target, and, in fact, he may have a separate display on another CRT which can show range on a simple Type A display; but in war it is commonly necessary for a pilot to get instant indication of the elevation and azimuth of the target, without waiting for range. A disadvantage of such systems is that for a period between transmitted pulses the tracing-spot is stationary, and this light-spot represents, in intensity, *all* that is received and put on the CRT by the radar receiver. Thus all extraneous signals, including noise, are accumulated together in the spot, and the contrast between noise and echo may be poor. One way of overcoming this trouble is to have at the side of the Type C, say, a Type A display showing range. The operator can then 'strobe out' the desired echo on the range display, moving the strobe control as previously described, and then displaying the selected echo alone on the Type C screen. In some systems such strobing can be done automatically.

So far we have considered some displays which can be used by seaborne, airborne, or ground radar to show such factors as latitude, longitude, and height above ground. But already we have gained a hint of the way in which, if we rock or swing the aerial array, and keep it highly directional, we can arrange our CRT display to be in sympathy, and thus we can attempt to draw a map on the CRT screen. At quite an early stage in the development of radar it was appreciated that it would be a boon if the CRT could really draw a complete map, or if the trace and aerial could be so kept in step that echoes would show up *in their true position on a map of the area covered*, and not merely between some arbitrarily chosen co-ordinates.

Even the layman can read position immediately from the CRT which really does draw a map, the 'plan

position indicator,' or PPI. Theoretically this is one of those fascinating ideas which appear so simple that it should surely have been immediately obvious to 'them' when 'they' were inventing radar! Yet the PPI represents the results of some years of work in radar and in CRT development; and though it is now not difficult theoretically, it nevertheless presented many tricky problems for the manufacturers of tubes for the system, and it is still not easy to ensure that tubes stay accurate over long operational periods.

When we look at a typical ground-radar station using a PPI display we see a fascinating picture at the tube end. We see, first, a translucent screen, squared off probably in graticule fashion, and the centre of this is not only placed over the centre of the CRT screen, but represents geographically the position of our station. On this graticule will be drawn, in black line, an outline map of the whole area, to north, south, east, and west of our station, and we must imagine that our radar transmitting and receiving aerials (if, indeed, a common-TR array is not used) are about to be swung, say, in clockwise fashion, looking out along a narrow beam, and with this beam being swung round in a full circle of 360 degrees.

On our CRT the trace is arranged to run from the centre of the tube to the outer edge, and, of course, this trace represents the maximum range of the equipment, just as in Type A. The tube is intensity-modulated, so that if an echo is received back along this particular line of shoot it will appear on the tube as a bright spot. We now set our aerial beam pointing, say, due north, and adjust our CRT so that the trace is also running from the centre of the tube to a position off the tube in the '12 o'clock,' or north, position. If any aircraft is flying along that line we shall be able to see its exact position

on the translucent map. As the light from the spot is not sufficient to illuminate the map itself subdued amber lighting may be arranged through the glass walls of the CRT, so that the map area is bathed in soft reddish light, and the tracer-spot shines brightly in green if there is an echo.

Reception along only one line would be of little use; but if we arrange to swing our aerial slowly throughout the entire 360 degrees, and move the trace clockwise round the tube end in step with the aerial, then any echo over the whole area will show up on the tube in approximately its relative position with respect to the centre, which, of course, is the position of the radar station. As the aerial sweeps the circle the trace is arranged to sweep the tube end in sympathy with it, and thus the faint line of light of the trace represents the aerial T and R beams. Intensity modulation causes the trace to brighten at a position relative to the actual distance of the object from the transmitter.

If the eye were not confused by persistence of vision, and if a longish-afterglow tube were not used in order to build up a coherent picture, then it would be possible to see the tube covered by a series of radial spokes, each spoke representing one single trace. The angle between the spokes is obviously directly related to the PRF, as the traces are not superimposed, but spread out according to the number of pulses per second. In practice the aerial may rotate a dozen times a minute, or as fast as 500 times a minute, and the trace is pulled round in step at the same speed. Afterglow and persistence of vision make it difficult for the eye to follow the movement of the light-line of the trace itself, and the echoes show up as bright spots or smudges. As the trace is 'moving' there is an optical tendency for these spots to appear not as circular pin-points, but as sausage-shaped blobs of

light, being, in fact, two or three echo spots on two or three traces in succession. As the transparent map is superimposed over the tube end these spots give a ready indication.

Obviously the construction of a CRT for PPI display must be different from that for Type A, for example. No longer do we have a stationary trace, with an echo deflected. The usual arrangement is for intensity modulation to be applied by varying signal voltages on the grid of the CRT. That produces for us our brighter spot on the reception of a signal. The time-base trace is arranged, by construction of the electrodes, to run from the exact geometric centre of the tube to the outer edge, and magnetic coils outside the tube itself (usually placed quite close to a long neck) 'pull' the trace round through the 360 degrees.

The coils produce magnetic deflection of the spot to form the time-base trace, and if they are mounted on a ring concentric with the axis of the tube, and are swung round, then the light-line of the time-base will be drawn round too. The coils in their mounting can be linked directly, mechanically, with the rotating part of the aerial system, but backlash may be experienced if the distance between aerial and PPI tube is considerable. In many systems the aerial and PPI coils are linked electrically, and an accurate follower-motor drives the coils in step with the aerial beam. In small radar outfits, if the PPI is not more than a few yards from the aerial, a flex drive is satisfactory. Rotation can, of course, be in clockwise or counter direction, and some systems have a reverse switch, so that either direction can be used at the whim of the operator. Continuous rotation is general, but with some search systems, where a full 360-degree cover is not essential, the aerial and the PPI coils may be swung over a small arc.

Many PPI tubes are for direct reading on the tube end, but the Skiatron-type projection can be used to display the map picture on a large screen.

From the manufacturer's viewpoint the PPI presents problems of alignment and so forth which can fairly easily be corrected in a Type A display, but which may cause errors in operation as the time-base itself is being swung round the clock. Manufacturing problems, however, are not so serious that they detract in any way from the amazing ingenuity and usefulness of PPI display, which in itself was the first full attempt to make radar 'draw its own map,' second by second.

VIII. CENTIMETRIC TECHNIQUE

FROM THE EARLIEST DAYS OF RADAR SIR ROBERT Watson-Watt had realized that greater accuracy, and in particular the capacity to discriminate between natural echoes and those from the target, was required. Nothing but a narrow beam instead of the former 'flood-lighting' could give the desired results, and this meant much higher power on much shorter wavelengths, with much higher sensitivity of reception. Fortunately Britain was well placed to deal with this problem, and from March 1939 some ninety of our leading physicists and men who had spent many years in the abstruse problems of splitting atoms and 'spinning' electrons were attached to the coastal radar stations set up to guard Britain against invasion. Their past experience had made them aware of the need for centimetric radar.

It is well worth while considering the history of this development, for it is to the exclusive credit of Britain, and is a development parallel with that of the harnessing of atomic power. Professor M. L. Oliphant, of Birmingham University, and Dr H. W. B. Skinner, of Bristol, inspired their co-workers by their insistence upon the urgent need for centimetric wavelengths, and by their own experimental skill. A tremendous drive followed, until in July 1940 Professor J. T. Randall, of Birmingham, produced the first workable directly excited cavity magnetron, the new and revolutionary type of valve for generating these extremely high frequencies. Randall's cavity magnetron was the first high-power generator of centimetric waves in the world, and the magnetron is likely for many years to remain the heart of every modern radar equipment.

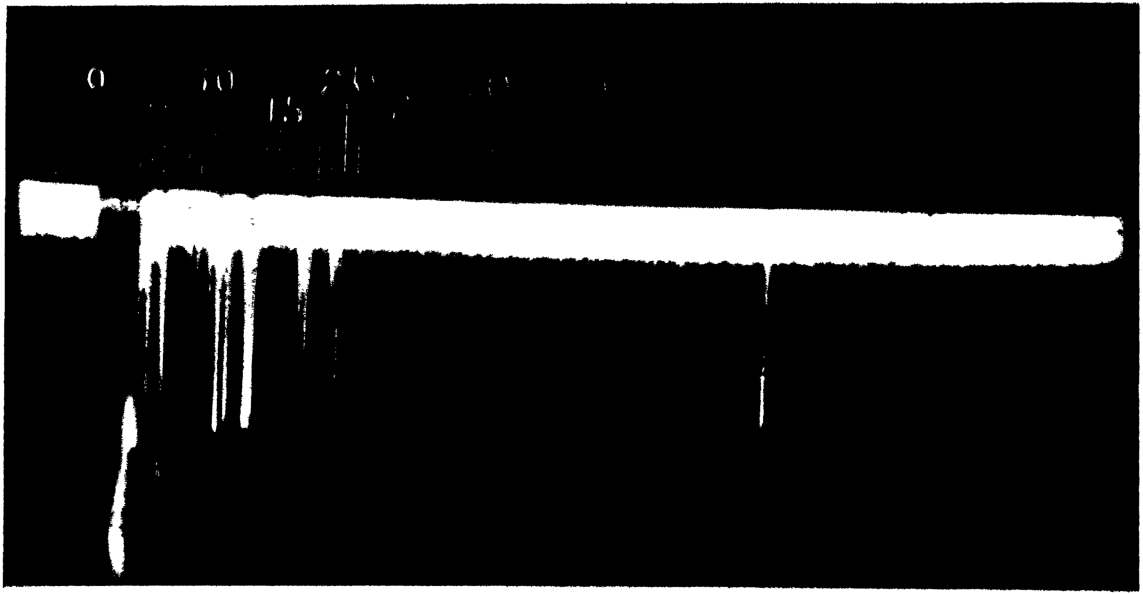


PLATE II: TYPE A RANGE DISPLAY

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[*See* Appendix, *p.* 169.]

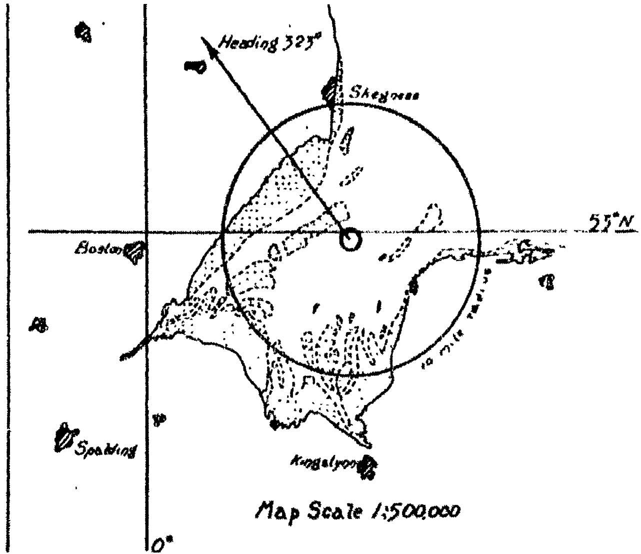

PLATE III: H2S SYSTEM: RADAR SCREEN AND TRUE MAP

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[*See* Appendix, *p.* 170.]

The magnetron was a spur to other physicists and technicians, and it was supplemented by an equally novel receiving valve evolved by Dr R. W. Sutton, and very soon remarkable radar circuits were developed to enable these new creators and receptors of ultra-high frequencies to be used to best advantage.

For a detailed study of the progress in development of these valves and other generators of very high frequencies I recommend reference to the Institute of Electrical Engineers Radar Convention papers, especially *Work on the Cavity Magnetron*, by J. T. Randall and H. A. H. Boot, and *The High-power Pulsed Magnetron*, by W. B. Willshaw and L. Rushforth.

'Centimetric,' where radar wavelengths are concerned, means a range of usually 3 to 10 centimetres, although systems using even shorter wavelengths are now in use, and the trend is towards higher frequencies still. The practical limits of standard centimetric equipment, however, remain 10 centimetres (frequency 3000 megacycles) and 3 centimetres (frequency 10,000 megacycles). Use of these shorter wavelengths allows the production of a very narrow beam without the use of very cumbersome and complicated aerials and reflectors. There is, perhaps, an apt parallel in sound and light. Wavelengths of sound, in the medium of air, are extremely long compared with the wavelengths of light in the 'medium' (if any) of ether. It is possible partially to direct sound by means of reflectors, but in no easy way can a very narrow pencil of sound waves be produced as can a ray of light.

That revolutionary new circuits must be employed in centimetric radar is obvious. A medium-wave broadcast receiver has tuning coils of normal dimensions, with probably a hundred turns of wire on a former an inch or so in diameter. In a short-wave set the tuning

coils may have only a dozen turns of wire. In a television receiver for use on about 7 metres we are reduced to only a minute tuning 'coil,' and for still shorter wavelengths we arrive at one turn or less of wire. In centimetric radar it is obvious that the shortest connexion between components must be longer, electrically speaking, than the wavelength 'carried.' If we cannot have a coil less than about a quarter of a turn, then we must find some other means of inductive coupling, and of generating oscillations. As we shall see, in place of a coil we employ a hollow space for the generation of oscillations!

In radar apparatus using such high frequencies the physical dimensions of the circuits are inevitably of the same order as the wavelengths, for it is difficult to visualize a circuit in which components are linked together by wires less than one centimetre in length. Thus every piece of the connecting wire will act like a portion of a transmitting line, and may radiate, with consequent loss of energy. Normal transmission lines between aerial and transmitter or receiver (as referred to in Chapter III) cannot easily be used, so we employ a long, hollow tube of metal as a conduit down which the electromagnetic energy flows as in a pipe—or, rather, one would like to *think* as in a pipe: the actual direction of flow of the energy in such a conduit is extremely complicated, and is the object of much difference of opinion among radar technicians. Conduits of this nature are known as wave-guides, and their cross-sectional dimensions are of the order of half a wavelength, for mathematical reasons we need not explore here. Thus centimetric radar sets working up to 10 centimetres can have wave-guides which are, in fact, not much bigger than household drain-pipes, and the energy is literally 'piped' from T to aerial and from aerial to R.

Electrical losses in these wave-guides are very small, and their efficiency at such high frequencies is much better than could be achieved with normal aerial transmission lines.

Radio enthusiasts are all too familiar with the difficulties of using normal valves at very high frequencies. A grid may be spaced about $\frac{1}{8}$ inch away from an anode in a broadcast valve, and the physical dimensions of the electrodes are such that we do not need to worry about them in the circuit constants, nor do we need to take any special care about the inter-electrode capacity set up through the electrode spacing. But when we want to use such valves for the generation or reception of very high frequencies we find that the capacity inside the valve itself may have an appreciable relation to the external capacities in the circuit itself, and unless we can reduce or neutralize them we shall find that the valve capacity stops the oscillation. While some 'normal' valves will work up to about 50 megacycles, it has usually been necessary to use special ultra-high-frequency valves even for the frequencies such as 56 megacycles, which in pre-1939 days were considered high. For reception the midget 'acorn' valves were developed, both as triodes and as pentodes. These were physically very small, and while they had closely spaced electrodes the area was small, so that the total internal capacity was low. Also these valves had no base, the connexions being brought out to short wire pins arranged in a glass ring about the centre of the valve. All this helped to cut down internal capacity, and, in fact, the first radar receivers built in 1939 used these acorn valves in some stages.

For centimetric radar even the most efficient ultra-high-frequency valve of normal construction is useless, because an entirely new factor is involved—the troublesome factor of 'transit time.' With centimetric waves

the frequencies of operation are so high that they bear some relation to the speed of the electrons travelling from cathode to anode of the valves. In a normal valve on normal wavelengths the familiar theory of operation takes for granted the fact that the electrons emitted by the cathode, controlled by the grid, and attracted to the anode will have time to make the journey and do their job. Indeed, in normal working the electrons travel with the speed of light, approximately, and one does not have to consider, say, placing the anode very close to the filament to ensure that the electrons will have time to make the journey before the next half-cycle of oscillation! But in centimetric radar that is precisely our problem. We can control the electron speed, within limits, by the applied voltages, and it will be realized that if we control the electrons to travel with the speed of light, then the distance travelled in one time period would be equal to the wavelength of the applied oscillation. If the wavelength is only 3 centimetres, then obviously this bears relation to the physical dimensions of the valve itself. We can, in fact, work out the distance travelled by electrons when sped on by a variety of voltages, and we find that at a wavelength of 10 centimetres the distance travelled in one time period is 2 millimetres for an electron urged on by 100 volts. If we put the voltage up to 10 kilovolts, then the speed is so increased that the distance travelled in that same time is 2 centimetres. In only a tenth of this distance the phase of the applied voltage will have shifted by 36 degrees. In an ordinary valve this means that an appreciable part of the oscillatory cycle occurs while the electron is crossing from cathode to anode, and so the ordinary type of valve with wide spaces between electrodes is useless for centimetric work. It is necessary for us to use an entirely new type of valve for oscillations at 3000 megacycles a second, and

in these valves the electron stream is caused to excite the oscillatory circuit by a mechanism which, indeed, makes use of the finite times of travel of the electrons.

The general name of these generators is 'hollow-space oscillators,' and in this class come the magnetrons, the klystrons, Heil tubes, and other devices, detailed description of which is in many cases impossible, for, like the precise details of the harnessing of atomic power, they are still a part of secret State information.

But just as high-frequency electromagnetic energy can travel through the 'pipeline' of a wave-guide, so oscillations can be created in a hollow space. If you picture a chunk carved out of a block of metal, forming a spherical space with only a very small opening, then you can imagine inside this cavity currents circulating on the inside of the opening, and associated electric and magnetic fields inside the cavity.

This is a startling conception to the man accustomed to the normal theory of oscillatory circuits with inductances and capacities, but in centimetric radar we have started along a new avenue of radio physics. In a radio valve we heat a cathode, emit electrons from it, apply a voltage to the anode, and the electrons complete their journey. But what would happen if by some means such as applying a strong magnet to the outside of the valve we *prevented* the electrons from completing their journey? We might thus visualize setting them whirling round in a circle, and in the magnetron that is exactly what we do.

On first switching on an anode voltage is applied, and the hot filament emits electrons, which do not, however, succeed in completing their journey to the anode. This anode we arrange as a large metal ring around the cathode, and we surround the whole with a powerful magnet, and whirl the electrons out of their course.

So fierce is this whirlpool of electrons that we can switch off the filament almost immediately, and, provided the magnetic field is maintained, we have a stream of electrons continuously whirling around inside the metal anode ring.

On the inside of this ring we cut a number of cavities, and the electrons pulled out of their course by the magnetic field parallel to the axis of the tube commence travelling across the openings of these cavities in a series of curved orbits. In this way appropriate charges are produced on the anode segments, giving rise to sustained high-frequency oscillations inside the cavities themselves. To link each cavity with the next the magnetron is 'strapped' with short stubs of wire carefully arranged so that the potentials from cavity to cavity are in the correct order. Small holes are bored in the otherwise solid block of the magnetron's main construction, and short lengths of No. 22 gauge copper wire are used as straps. In manufacture these straps are used for pre-tuning, for obviously the magnetron is otherwise limited by its solid construction, and no great variation of frequency is possible. Continuous-wave energy from another source (usually from a klystron) is injected into the magnetron through the coupling loop, and the coupling straps are then bent up, down, or sideways until the whole is resonating at the desired frequency. Tuning is not otherwise usually attempted in magnetrons, although in one type of equipment there is a tunable magnetron giving a possible variation of about 75 megacycles either way (at some 3000 megacycles), and this tuning is achieved by making the lid of the magnetron itself of thin metal, so that the centre can be depressed on a screw-thread and the internal capacity of the segments varied by a small amount. Experiments have also been carried out with tunable magnetrons having metal rods

capable of being moved in and out of the main anode block.

The klystron is another variety of 'hollow-space oscillator.' Picture a CRT in which a beam of electrons is drawn from the cathode to the positive anode. On their way the electrons pass the lips of two rhumbatrons —ring-like cavities connected together by concentric pipes. The first cavity is known as the 'buncher,' as the physical dimensions are arranged so that the electrons do, in fact, cross the opening of the cavity in bunches, in alternate 'parcels' of large and small electron density. Then follows a 'drift space' before the electrons cross the opening of the second rhumbatron cavity, known as the 'catcher.' The bursts of electrons passing between the two cavities set up oscillations within. If you picture the whistle set up by blowing across the lip of holes in a penny whistle you will appreciate to some extent how the klystron oscillates. The blast of air corresponds to the stream of electrons, the holes in the whistle are the lips of the rhumbatron cavities, and the resulting sound is the oscillation in the tube. But in the klystron the holes are at right angles to the main electron beam, and the oscillations do not take place near the beam, but inside the rhumbatron rings.

There is a second type of klystron known as the reflector, in which there is only one rhumbatron cavity, which acts both as buncher and catcher for the same electron beam. On their first traverse past the lips of the cavity they are velocity-modulated; they are then reflected back, and on passing the cavity a second time are density-modulated. The effect, of course, is precisely the same, the electron gun setting up oscillations within the rhumbatron cavity. There are several modifications of the reflecting klystron. In one form the reflecting electrode is negative, and repels the electrodes

shot at it by the 'gun.' In another type the reflector is strongly positive, and by secondary emission produces a counter-stream of electrons. Such klystrons are quite small, and often have a standard valve base to which is attached the electron gun. The rhumbatron cavities are formed by copper rings or discs, and to some extent the device is tunable by a screw-plunger regulating the capacity of the rhumbatron, affecting its volume or shape. Klystrons are producers of lower-power oscillations at very high frequency. Their efficiency cannot very well be high, for it is physically impossible to ensure that all the electrons pass through the rhumbatron in both directions. With the first types of klystron developed a radio-frequency output of not more than a tenth of a watt is obtained from 10 watts input.

The Heil tube is another form of velocity-modulated radio-frequency oscillator. Electrons are emitted from a cathode and pass through a grid on their way to the collector, this grid playing no part in the creation of ultra-high-frequency ocsillations, but controlling the total current. The beam of electrons passes through two slots in two concentric tubes placed at right angles to the flow. These tubes are really the two parts of a concentric transmission line, and the radio-frequency oscillations are set up at the slits through which the electron beam is directed. The concentric tubes are connected to the output circuits by a concentric feeder-line, but there is an alternative form of Heil-tube construction in which one part of the concentric feeder projects through the glass tube, and it can be tuned within narrow limits by an external extension. Theory of the Heil tube is somewhat complicated, but is a parallel with that of the klystron and Sutton tubes: it has been said that the gap between the outer tube and the inner is in effect the 'velocity-modulating' space, the space inside the inner

tube is the 'drift' space, and the second passage of the electron stream through from inner to outer concentric feeder is through the catcher space. Heil tubes can be used to give an output of some ½ watt, but again the efficiency is very low, usually not more than 5 per cent.

Although tubes of the klystron type handle such low power that they cannot be used as oscillators for microwave radar transmitters, they can be used for the equally important purpose of acting as local oscillators in the receiving end of the chain.

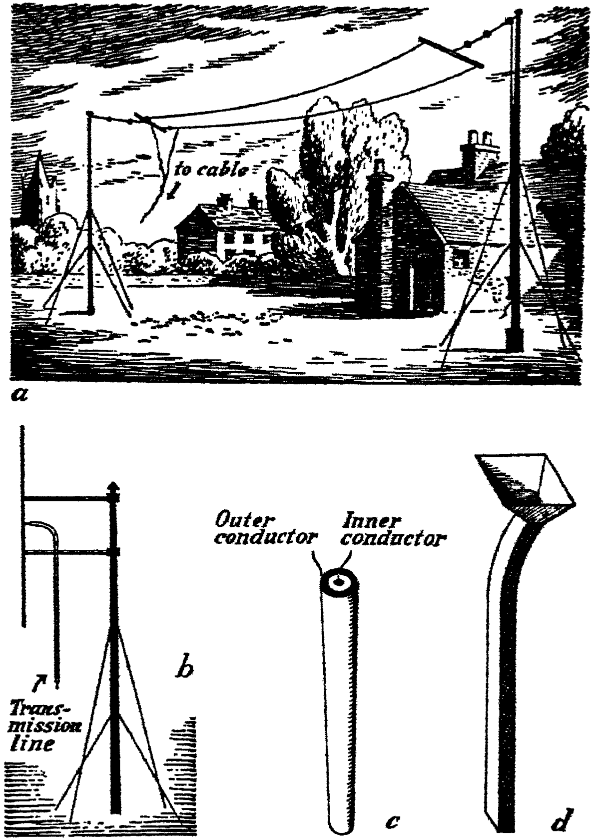
On these very tiny wavelengths no signal-frequency amplification is possible, so the first stage of almost any radar receiver working on less than 10 centimetres consists of the mixer, into which (as in normal broadcast practice) the signal voltage and the voltage from a local oscillator are fed. In centimetric equipment the local oscillator is usually a klystron, and the mixer used is either a simple diode or a crystal capsule. It is somewhat ironic to return to the crystal detector in this advanced phase of radio technique, but although the research organizations of the G.E.C. and Mazda have produced very efficient microwave diodes as mixers, much radar equipment at present in use has a crystal-mixer capsule; and the mixer, whether it be crystal or diode, is inserted usually in the concentric transmission line itself.

The capsule is mounted in a high-impedance section of the transmitter line, and into the same compartment are fed the 'pipes' bringing in the e.m.f. from the klystron local oscillator, and also those leading to the first IF stage of the centimetric superhet. A silicon crystal and a tungsten wire are used as the rectifying contacts, and with correct adjustment this gives a 'back-to-front' ratio of about seven. The crystal and contact wire are mounted up in the capsule, which forms an

integral part of the transmission line, and when the contact is satisfactory the whole capsule is filled with molten wax to stabilize the crystal against vibration. These crystal mixers are very efficient, but are apt to burn out easily and lose sensitivity if excessive voltage is applied to them. For this reason special precautions must be taken with centimetric radar when using a common aerial for transmission and reception to ensure that none of the transmitted signal energy is accidentally passed to the receiver feeders. Diode mixers can withstand a greater overloading, and do not need to be so elaborately protected against the transmitter signal voltage.

Energy is piped to the aerial array from the transmitter, and back to the receiver, by means of waveguides. Until about 1936 the only means for linking radio equipment to the aerial was by means of a *pair* of conductors. We had parallel pairs of transmission lines, twisted wires, and then 'coaxial' feeders consisting of a wire or tube inside another tube. The operation of all these circuit means of transmitting radio-frequency energy by wire can be studied by amateurs in such works as *The Amateur Radio Handbook*. The very latest centimetric radar equipment has rendered such circuit methods of connexion out of date, and all 'circuit' theories have had to be discarded in favour of the idea of wires *guiding* waves of energy in the required direction, rather than acting as parts of circuits linked to the 'lumped' circuits of the apparatus itself.

So just about ten years ago radio experimenters were attracted to the possibility of using metal tubes filled with some insulating dielectric as 'guides' for electromagnetic waves. Almost at once it was realized that a 'hollow' tube—*e.g.*, filled with air only—was satisfactory for the purpose, and that waves could in reality be



TRANSMISSION LINES

For wavelengths above about 50 metres the length and nature of the line connecting the transmitter or receiver to the aerial is of little relative importance. Below 50 metres the aerial and line must be shorter, but are still not a cause of serious loss until we reach about 10 metres. (*See* (*a*).) For wavelengths from about ½ metre to, say, 10 metres the transmission line (*b*) must be suitably chosen. Long transmission lines are made of concentric cable as suggested in (*c*), in order to cut down attenuation losses. For centimetre waves concentric cable causes too much loss even on short lengths, and the connexion between transmitter and 'aerial' is a wave-grade of rectangular section made of copper sheet (*d*). It can be bent, and it can be flared into a horn to project the waves against a metal reflector.

Note. The drawings are merely illustrative, and are not to be considered accurate in detail.

guided along such conducting tubes with negligible loss. The energy does, of course, continue to travel along the 'pipeline' of the guide in wave-form, just as it would, according to one school of thought, travel in free space by radiation. The important difference—and, indeed, the factor which makes the wave-guide a workable proposition for radar—is that the strength of the waves in free space falls off as the reciprocal of the distance, while, in a tube made of a perfect conductor, there would be no reduction in strength as the wave-form travels along the tube. In practice, using copper tubes as wave-guides, the attenuation is about 20 per cent. for 50 *yards* of the guide. As few guides are more than a few yards long, this loss is unimportant.

By careful design it is possible to introduce even sudden bends into the guide, and when it is required to radiate the microwave energy into space the wave-guide itself is simply opened out into a 'flare,' or horn. This horn opening may face a reflector, of course, to direct the energy and thus to beam the transmission. If the guide is not used to terminate in a radiator, then energy is fed in by a small aerial stub at the start of the tube, and taken from the far end of the tube by a similar stub. The majority of guides used in radar equipment are of rectangular cross-section, to ensure greatest accuracy in design, and also, so the cynics would say, to simplify the mathematics! The 'arithmetic' of this form of link does, in fact, become quite complicated, because mathematical analysis shows that only certain types of wave-forms can be propagated along metallic wave-guides, and each of these wave-types, moreover, is characterized by a certain distribution of electromagnetic field over the cross-section. The velocity of the waves is different from that in free space, so the wavelength in the tube is somewhat different from the length in space, and this

velocity change depends not only on the frequency of the transmission, but on the cross-sectional dimensions.

It is unfortunate that at this stage in the world's history only an approximate picture can be given of centimetric equipment, for each nation has its radar developments, and all progress is largely State-sponsored or State-controlled either for supremacy in civil or military aviation or the guidance of projectiles.

But it is fitting to conclude this brief survey of centimetric devices with a final irony. We have seen how scientists have had to revert to the use of the crystal detector as a mixer in centimetre superhets. And the early pioneers of radio, who remember Marconi's 'S' spark signals from Cornwall to Newfoundland which made history in radio communication, will smile on investigating the spark-gap modulators used in many microwave radar transmitters.

We have seen that radio-frequency oscillations can be produced by a device such as the magnetron, but these oscillations are of sine-wave form and must be modulated by square-topped pulses of e.m.f. at high power to produce radar pulses in free space. These square-topped e.m.f.'s are commonly produced by suitable arrangement of a transmission line into which energy is fed, and the wave-form is distorted to produce a square top. But we need a switch to throw this special section of the transmission line in series with the load, to modulate our centimetric oscillations; and the two common types of switch are the thyratron (with certain modifications such as the trigatron) and the ordinary spark gap!

Both such devices depend, of course, on the fact that an electric discharge in a gas provides a conducting path. The operation of the thyratron we have investigated; the trigatron uses a gas filling of argon and oxygen. But

the spark-gap modulator bears striking resemblance to the spark-gap Hertz transmitters of pre-1914 days. It is not suitable without modification for airborne radar because of the effect of atmospheric-pressure changes on the gap. There is a rather more elegant version known as the triggered gap, in which the discharge takes place between a metal cathode and a hollow tubular anode, usually of molybdenum. The gap is set up so that normally it will just not 'strike' until a trigger electrode (usually a rod in the centre of the hollow anode) is connected, thus closing the switch. This centre electrode is connected to an additional valve circuit providing low-power pulses to close the circuit at predetermined intervals to provide the PRF.

IX. THE TASK AHEAD

IN THE PRECEDING CHAPTERS WE HAVE WATCHED THE fundamental points of radar, and have seen how the basic systems work. Now we can study in more detail the systems developed since the War, and look ahead to the new tasks facing radar. It must be remembered, however, that the picture is rapidly changing. New applications are being found for radar, new systems are being pioneered, and with almost equal suddenness political changes take place which make some systems of more importance than others. In radar, which spans the globe, there can be no frontiers, and politics naturally enter into the good-neighbour applications of radar systems intended for international aviation and marine transport.

During the war years we heard much of H2S, Gee, Oboe, Babs, Eureka, Loran, and other systems. In subsequent chapters we shall investigate these systems and see how they work and what they provide both for military and peacetime needs, but this is an appropriate moment to put some of these systems in their proper perspective. Obviously the technical ingenuity of radar will be productive of systems to aid safer, swifter transport. But pulse-system radar is not the only technique which can be so applied, and there is a considerable future for systems such as the QM (Decca) and the Console, which are 'radar' methods in the generic sense, but which are not pulse methods; their background is the normal continuous-wave transmission. In many navigational problems they provide a much simpler solution than pulse radar, but some believe that in their

present state of development continuous-wave methods have certain disadvantages where long ranges have to be measured accurately. "It is possible, for instance," as a writer in *Nature* points out,

> for continuous-wave systems to be confused by spurious readings caused by near-by objects, and these local obstacles tend to reduce the usefulness of continuous-wave systems, despite their great accuracy. With pulse radar we can choose suitable transmitting frequencies and introduce other methods, so that scatter from the ionosphere and reflections from near-by objects can be ignored.

It is possible to suppress PE's to a certain extent on the pulse system, so for some navigational purposes ranging and direction-finding by pulse radar are to be preferred.

In summing up the relative advantages of radar systems a Ministry of Aircraft Production Telecommunications official has pointed out:

> We have to remember that there are essential differences between war and peace transport needs. In the air, for instance, civil aviation is very largely concerned with the problem of economic pay-loads, which are not factors of great importance in war. In hostilities there is almost no ceiling to the maximum cost of delivering a bomb-load to an enemy objective. In war, moreover, it may be expedient to sacrifice bomb-loads in order that more adequate radar apparatus can be carried. In civil air transport passenger- and freight-carrying become uneconomic if undue space has to be given to radar apparatus, or if its weight is excessive compared with other navigational equipment.

Technical needs are very different, moreover: in war aircraft fly very largely over hostile enemy territory, where it is difficult for navigational aid to be given from the ground, and where even recognition of ground targets by systems such as H2S may be confused by radar

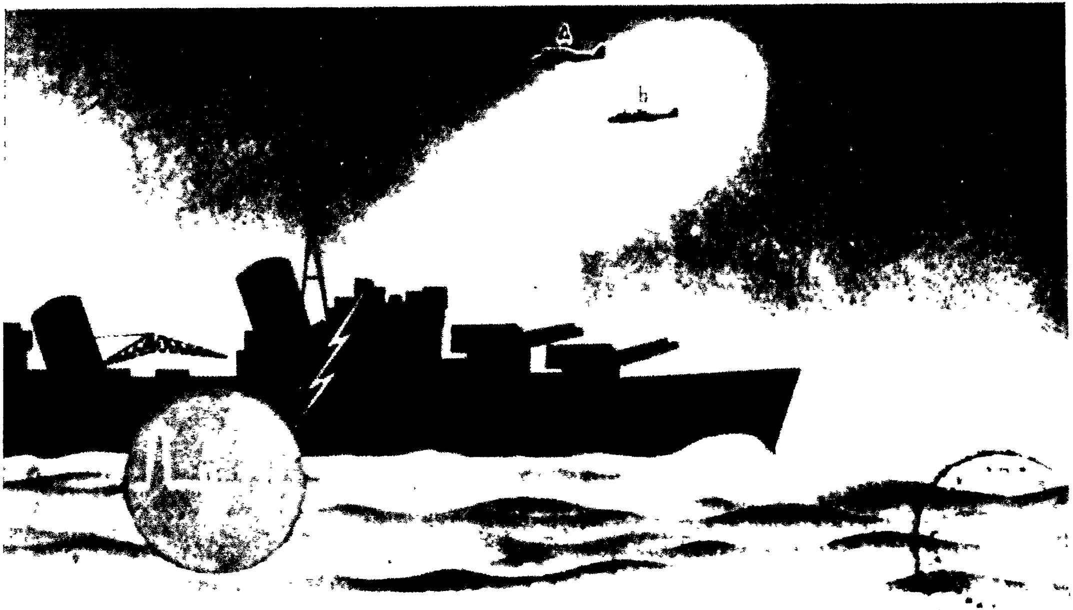


PLATE IV: MARINE RADAR

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(See Appendix, p. 170.)

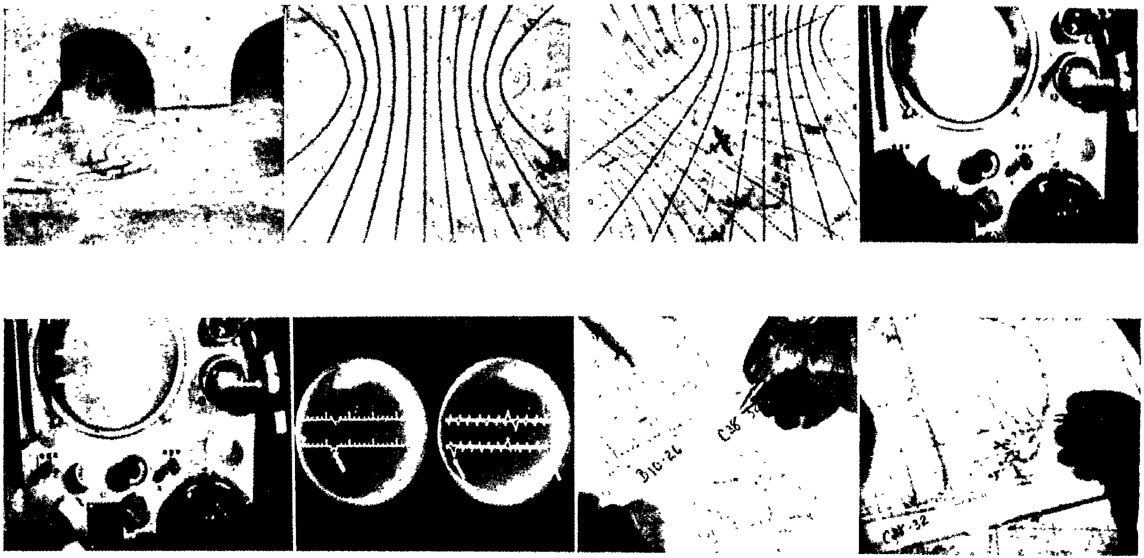

PLATE V: OPERATION OF GEE RADAR

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[*See* Appendix, *p.* 170.]

camouflage. The enemy does not post convenient radar beacons all along the route, but, of course, in civil aviation the ustmost co-operation can be expected from ground aids, and there is an entirely different prospect for aids such as radar beacons.

Wartime necessity for the radar navigation of British and Allied bombers at night over Germany brought about the Gee system, perhaps in its day the most extensively used of all radar non-echo navigational systems. As we shall see, Gee has a maximum range of about 400 miles. It set a completely new standard of accuracy in radio navigation when it was first introduced by the Malvern experts for Bomber Command, and heavy raids at night over Europe would not have been possible if we could not have covered Europe with the invisible but very tangible Gee lattices. Loran, the American long-range modification of Gee, working by reflection from the ionosphere, became very useful over longer distances of even up to 1000 miles, although it was conceded that over shorter ranges Gee was more accurate, and that Loran should, for all normal purposes, take up where Gee left off. With suitable international agreement both systems could be used with advantage, but, of course, in civil aviation we have no need to rely on the Gee or Loran lattices if the ground below can be adequately covered with radar or other beacons. The need for the lattice system is greater in war, except over large tracts of ocean where beacons cannot be installed except on bouys. It is too early yet in the history of radar development to tell if a sufficient number of radar beacons can be placed over the earth's surface to make other long-range navigational systems obsolescent under civilian conditions of air travel. For maritime use the position is different, as a radio officer would experience confusion from a large number of

beacons all at sea-level. This is not a difficulty which faces an air navigator, who may be able to gain useful guidance from ground beacons perhaps more than 200 miles ahead.

The Royal Navy developed several radar systems which now make a considerable step forward in marine navigation; and several types of semi-automatic radar gear are now produced for merchant-ships. A typical installation is that made for the whaling-factory ship *Southern Venturer*. This radar equipment was a naval warning set designed and manufactured in Canada. It gives a display on three PPI tubes, and, although originally designed to give warning of enemy ships, has now been harnessed to give warnings of icebergs and of other craft approaching at night or in bad weather.

One weakness in early systems was a difficulty of distinguishing between ships and buoys, but experts of the Admiralty Signal Establishment carried out tests on board H.M.S. *Pollux* in the Thames Estuary, using buoys provided with radar corner reflectors. Such buoys are now often laid in geometric patterns, and the extra response given back by the corner reflectors enables them to shine up brightly on the PPI screens, and in this way they are easily distinguishable from the pin-points of light which represent ordinary buoys and moving ships. In a restricted sea area of an approach to a large port the benefit derived from radar when used in conjunction with corner-reflector buoys can clearly be seen, especially in low visibility. Attached to some of the latest marine apparatus is a chart comparison unit. When a navigator has got his 'fix' by radar he must refer to his chart to get a sounding. In the comparison unit the image of the charts is thrown on the screen, and the navigator can at once compare his position and the sounding on the chart. In initial trials in the few years

immediately following the War there were differences between British and American marine methods, but the authorities in this country have worked hard to develop simple navigational ideas which have been given to all seagoing nations, and which may become international marine standards. This would be no more than poetic justice, for radar was so pre-eminently a British development, and we gave our allies in war the full use of our scientific research.

It is appropriate to mention that maritime navigation can hardly fail to benefit from Admiralty centimetric research during the war years: the greatest triumph of our surface gunnery was in the famous wartime *Scharnhorst* action, the first major naval engagement carried out entirely by radar. The combatants never sighted each other visually from start to finish, and the aid given by spotting aircraft was held over, as radar aid was sufficient for the action. It is to be anticipated that continuous-wave systems rather than radar will be of use in bringing vessels safely to harbour, and that non-pulse systems, as well as radar with corner-reflecting buoys, will guide ships safely along sea-lanes. It is interesting to reflect that the Decca system of continuous-wave navigation was used to bring small vessels into French harbours during the War, with an accuracy of yards.

Although airborne centimetric radar has great possibilities in peacetime civil aviation, it must be remembered that H2S, ASV, and other systems, which were among the most spectacular developments of war, are limited for civilian use. Military-type H2S is too complex, too heavy, and too costly for civilian use. At first sight it appears to offer the ideal radio aid to navigation, for it is a continuously running 'television' map of the ground, being a direct replacement for contact flying.

But many civil air experts believe that it is unnecessary to go to such lengths to produce a self-contained navigational aid which demands no co-operation from the ground. Absence of ground organization is essential in war, but in peace air lines travel over well-known routes, and can obtain all ground assistance. There is an obvious future, however, for miniaturized systems of the H2S type for exploration and for use over new routes.

"Obviously airborne centimetric radar is an aid to collision-warning," states a research expert of the Telecommunications Research Establishment, "but

> it does not at present appear possible to use radar as a collision-warning system for rail or road transport, as the necessary aerial arrays are too large and complex. There is, perhaps, a greater future here for supersonic methods than for pulse radar.
>
> Bad-weather flying involves risk of collision with other aircraft, with high ground, or with dangerous clouds. When direct control by radar of all aircraft within the vicinity of a busy airport can be effected all three collision dangers will be reduced, but until then there is much to be said for the safety given by microwave warning equipment in the aircraft. 'Mountain Goat,' a popular beacon warning system used during the war years for giving pilots radio-audible warning of dangerous high ground, can be extended to register on all civilian air radar. A difficulty with many existing radar systems is that they are really too effective for collision-warning, and give more information than the pilot needs. Any device which continually gives warning of anything but potentially dangerous aircraft would be a distraction, and therefore a menace, to a civil pilot.

We can easily see that among the tasks ahead for radar are many ancillary jobs, some of which we can regard only as curiosities. Canadian radar experts have done much useful work with a modification of ASV designed to locate shoals of fish swimming near the surface of

great Canadian lakes. It would be premature to anticipate too much success for underwater investigation by radar, and when the main job is locating submerged objects, then there may be a greater future for supersonic rather than electronic aids.

The Royal Society has amassed a considerable amount of data on the migration of birds, and now that we have discovered that large flocks of birds give a quite reasonable reading on the average radar equipment we could use radar technique to plot the course of migratory flocks, and thus discover much that organizations of bird-watchers might never know, when flocks cross large tracts of ocean. Ornithological research in the future can hardly be dissociated from radar, any more than can weather-forecasting.

Radar meteorology, however, must be along two lines of development. In the tropics we have found that sudden changes in air-pressures, in humidity, and in other meteorological conditions produce widely differing results on radar apparatus. We therefore have to use expert forecasts to know what effect the weather will have on radar itself, and in turn we can use radar to find out what sort of weather is to be expected in the immediate future!

The radio-sonde (radio-transmitting weather balloon) now has a useful colleague in the weather balloon fitted with simple radar reflectors, the course and height of which can be spotted in a few minutes by relatively simple ground radar apparatus. Rain-clouds can also be plotted on some centimetric radar equipment, and, indeed, greater accuracy of weather forecasting may become one of radar's valuable contributions to navigation, a contribution as great as that given by radar in more direct aids to marine and air transport.

Now that we have studied the basic principles of radar

equipment we can progress to a more detailed investigation of practical systems. We can see how the leading marine radar systems have developed from basic equipment. In airborne centimetric systems we can investigate such devices as H2S. In navigational systems we can investigate Gee, Oboe, G-H, and Loran, and a wide range of beacon-direction, blind-landing, and height-indicating equipments. All these things have one thing in common: they depend on pulse transmission, though not in every case on echo reception.

X. THE MAGIC EYE

OF ALL RADAR SYSTEMS PERHAPS THE MOST COLOURFUL in its practical application is that branch of airborne centimetric radar known by the generic code-name handed down from the war years, H_2S.

This is the 'television' airborne radar system which on a PPI tube gives a very reasonable map of the ground over which the aircraft is flying. Variations of the system were used during the war years for ASV search, as the system which can 'draw' a map of the ground can equally show up vessels on the ocean surface below. With early H_2S technique the map was little more than a skeleton, showing the main features, towns, rivers, and coastlines standing out clearly. With later systems it has been possible to 'draw' the map with a narrower beam of radiation, and thus to give more detail in the picture. It is not unreasonable to suppose that development along these lines could produce an H_2S-type equipment capable of showing almost as much detail on the ground, from a height of, say, 2000 feet, as does a television picture on the 405-line system. This would appear to be the ideal navigation system, needing no co-operation from the ground, and being controlled entirely by the pilot or navigator, so necessitating no interpretation of instructions. It seems unlikely at present that H_2S-type systems will offer great scope for civil aviation, owing to cost and weight of equipment, but for special tasks H_2S may be the only solution. For radar cartography, for instance, H_2S is an accurate check. Directions given to radar aerial-survey units from Oboe and Gee stations can be checked on the spot by H_2S, and for

scientific work of this nature the weight and cost of th equipment are not a serious disadvantage.

H2S could not be conceived until it was possible t transmit radar pulses on wavelengths of a few centi- metres, instead of about $1\frac{1}{2}$ metres. Radar systems mus obviously work to fine limits if any attempt is to be mad to draw a map of the terrain below by means of a con- centrated beam of energy. It was known by Sir Rober Watson-Watt's workers as early as 1935 that suc reflections from the ground could be displayed, perhap even in map form, but the lack of a high-definition trans- mitting system prevented anything being done whic would at that time have been of operational value. Bu immediately centimetric radar could be airborne great future opened up for systems such as H2S, becaus the requisite narrower beams and sharper pulses coul be produced on the centimetre wavelengths.

H2S and all the systems such as ASV, which give i the aircraft cockpit a television-like picture of the terrai below, took their rise in the fateful autumn of 1941. Th comparative failure of our bombing effort over German at that time was very much in the minds not only of th operational Service heads, but of the technicians respon- sible for the radar devices then in use. A different typ of blind-bombing device was needed, which would b relatively immune from enemy jamming and whic would be self-contained in the aircraft, demanding n co-operation from ground stations. The success of air- borne radar in fighters over home territory in wardin off the threatened attacks of enemy bombers and nigh fighters led T.R.E. technicians to explore other possi- bilities of such airborne radar.

They soon appreciated that the new airborne syste with very little modification might be used to detect no air targets, but ground targets. 'Ground returns,' th

wasteful, troublesome echo returns from the ground, inseparable from early types of airborne fighter equipment, where part of the radiation reaches the horizon and the ground, and so clutters up part of the display by unwanted 'earthy' echoes, might at last be harnessed to use.

The beam of radiation which had in the past been used to search the sky for hostile aircraft could now be made to search the ground for towns, factories, and other solid objects which it was soon discovered gave a rather different sort of echo back from that of the flat surrounding earth or sea. These built-up areas might thus be displayed on the CRT as 'targets' against the weaker response from the open country. That such a method of detecting towns was possible had been demonstrated previously, using a system on 1½ metres, as described in the first chapter of this book. But on this occasion only very isolated towns could be picked up and located, owing to the overlapping of the responses from hills and woods included in the 'illumination' of the ground by the relatively broad transmitted beam. Even at that early date British scientists could see that, given a higher-frequency transmitting system to produce almost a pencil of radiation, more detailed illumination of the ground could be achieved, and then a cockpit 'television' picture system might be devised to show a useful map of the ground.

But the autumn of 1941 demanded immediate operational results, so an aircraft was adapted for 'downward-looking,' with a bowl-shaped reflector pointing towards the ground; this showed immediate promise on its first test flight from Christchurch to Wolverhampton, in that a series of 'target' towns and other objects were seen on the radar display, and after the flight it was found possible to correlate these with specific objects on the

known route. This one test was enough to convince the scientists that it would be worth while building a specially designed radar transmitter and receiver for ground search.

Very soon it became obvious that this system could be used to build up for the navigator on his radar screen a map of the terrain, for there were sharp differences in the responses from flat country and built-up towns, and again between land and sea. On the radar screen man-made objects, such as factories, show up very strongly, the radar echoes back from these objects (with their very numerous walls and reflecting surfaces) being powerful. Reflections from land are much weaker, being slightly diffused, whereas the flat surface of water gives almost no reflection at all back in the direction of the aircraft.

The decision to install this new aid soon followed; production on a superlative scale of speed and priority, under the personal urge of Winston Churchill, was the greatest of all 'crash' programmes of radar production, but it was vital to keep the enemy in the dark about the purpose of this novel device, even when he had some evidence that new fittings were appearing in our aircraft. So it was to be known as a 'homing device.' The initials BN, for 'blind navigation,' by which it had been known, were thought too suggestive, and as a name which would give nothing away, H_2S was suggested; and H_2S has thus come to be the general title for all such equipments. There is an amusing story told that on first being given an aircraft with experimental H_2S a navigator returned, and, asked for his opinion on the new device, cautiously and conservatively preferred his former means of navigation, and compared the new one to the H_2S (hydrogen disulphide) of our schoolboy 'chem'-lab days, saying bluntly, "It stinks!" But in point of fact H_2S was one of the very few radar devices which were reasonably

successful from their inception, and navigators did, indeed, welcome this new aid with enthusiasm and with complete lack of odious, odorous comparison.

In H2S the aerial system is placed inside a turret or streamlined Perspex 'blister' under the belly, and pointing in a directional sense towards the ground. The aerial and reflector are placed so that they can rotate about a central vertical axis.

A cut-down parabaloid shape is achieved by skilful metal-beating, and the dish-shaped aerial system results in a beam narrow in azimuth, where the reflector has its full dimensions. In elevation the beam is spread out in such a way that, although most of the energy is sent out at a few degrees below the horizontal, the lobe is deformed at greater angles from the horizontal. It is therefore not quite correct, in practical forms of H2S, to think of the radiated energy as being strictly a 'pencil' of rays illuminating the ground. But sharp beaming in this complicated pattern is necessary to ensure a deformed lobe of correct proportions, so that an aircraft receives echoes back of approximately equal strength from all targets within range.

This beam is rotated by the physical movement of the scanner, with reflector and director, and in the earliest systems the aerial itself is of the half-wave type, at the focus of the scanner, and it illuminates a strip of the ground at any one time, in the shape of a sector of a circle not much more than 5 degrees wide. The most remote point of illumination is controlled, so that the H2S can scan over, say, ranges of 50 miles, 20 miles, and 5 miles, and at each setting a full-diameter circle is displayed on the CRT. Obviously a PRF of over 500 must be used for such equipments, and the scanner is rotated at a speed seldom in excess of 1½ revolutions a second. The effective angle of inclination of the scanner

is varied, of course, to produce illumination at different ranges.

With basic types of H2S there is a common T and R aerial system, the magnetron and Sutton-tube local oscillator are used, and a 'gas-gap' switch to connect alternately the high-power transmitter and then the sensitive receiver and crystal mixer to the array. The gas gap consists of two electrodes in a soft valve. During the interval when the transmitter is not giving a pulse (or, as we say, when it is 'on space') the coupling loop of the system acts as a short-circuit, and the proportions of the rest of the feeder are arranged to be a quarter-wave line giving infinite impedance. In this condition only the receiver is electrically connected to the array. Immediately the transmitter pulses ('marks') the ionized gas in the gas-gap switch breaks down, providing an effective short-circuit. The gas gap is placed in the feeder system at such a point that the short-circuit of the gap transforms the receiver side of the feeder into a quarter-wave line, so this time the passage to the receiver is blocked by conditions of infinite impedance, and all the energy passes from the transmitter to the aerial. This switch-over takes place over 500 times a second, and if the gas gap of H2S were to break down or fail to work on any one pulse the receiver would be burned out. Precautions are taken, therefore, as in all similar centimetric aerial T-R switching devices, by inserting impedance transformations to give additional protection. Of all the practical modifications perhaps the easiest to follow is the application of a biasing voltage to the gas-filled tube. These small voltages are applied to encourage the gas gap to ionize as soon as the transmitter 'mark' begins, and ensure that the receiver side of the feeder is safely switched off.

The gas gap, therefore, enables pulses of energy to be

sent to, and echoes received from, the rotating H2S scanner. A rheostat control regulates the speed of rotation, as the wedge-shaped slice of illumination covers the terrain, and the trace line, as in all normal PPI techniques, rotates in step at the same speed. By displaying echo returns the H2S tube trace paints and continually repaints a map on the tube end. In this map the objects which send especially strong echoes back to the set, such as towns where there are many vertical walls and buildings, appear as bright spots. Water areas appear black, for they do not reflect any appreciable radio energy back to the sender, but reflect it away. In early H2S systems the picture was very liable to show underexposed areas or gaps. Contrast between town and country was not very great, and the picture obtained was what a photographer would regard as underexposed. Hours of patient experimenting in the air and on the ground have been necessary to get the correct grading of radiation at all angles from the scanner. The development of H2S has not been without loss of life. The first heavy bomber installed with H2S crashed on an experimental flight, and all the crew and five of the pioneer experimenters were killed.

What the H2S picture may show is not the scene immediately below the aircraft, but at some slant range ahead. Thus if the slant is known the height of the aircraft itself can be calculated, which is an additional navigational aid. But an electronic difficulty is encountered, for what we are chiefly aiming to show on the H2S tube is a true map-like picture of the scene beneath, and we must counter the distortion introduced by the differences in ranges, for a slant-range map introduces inaccuracies akin to perspective distortion. If we can calculate this distortion we can arrange to speed up or slow down the time-base itself at precisely corresponding

ranges. Thus, putting this solution to the problem very briefly, we can distort the start of the time-base to correct for the slant-range distortion introduced by the purely optical scanning differences in range. The result is a non-distorted map which does bear close relation to the geographic map. There are other visual distortions, of course, for the precise shape which a rectangular block of buildings takes on the PPI tube depends on certain factors, one of which is the range. Unless correction is made a rectangular target seen at a considerable distance on H2S equipment appears, not square, but 'thin.' As the run-up to the town is made it fattens up to its true proportions. This is because at long range the incident waves fall on distant objects from a direction nearly parallel with the earth's surface. Only the front, facing walls of buildings thus give any return to the radar receiver, and the rear walls are hidden from the beam. As the run-up is made the angle of elevation increases, and more walls and buildings come into the 'sunshine,' as it were, of the H2S pulses, and so can give an appreciable returned echo. Here, again, correction can be made electrically if necessary.

Obviously there is relation between the direction in which the scanner is 'looking' and the direction of the aircraft's travel, and here we have a choice of displays. Either we can arrange the H2S displayed map to be always with its top (on the tube) representing the direction of flight, or we might link the H2S display with the gyro-compass of the aircraft, so that the map is always pointed to true north. For civil aviation over considerable areas of land the latter system is to be preferred if it is possible. Over land H2S-type systems show up towns, large buildings, and prominent coastline formations. Over sea the kindred ASV enables the operator to see, as though plotted on a

chart, the positions of all ships and coastlines within range.

It gives us, at best, the sort of chart referred to in *The Hunting of the Snark*, the chart

> . . . representing the sea
> Without the least vestige of land;
> And the crew were much pleased when they found it to be
> A map they could all understand!

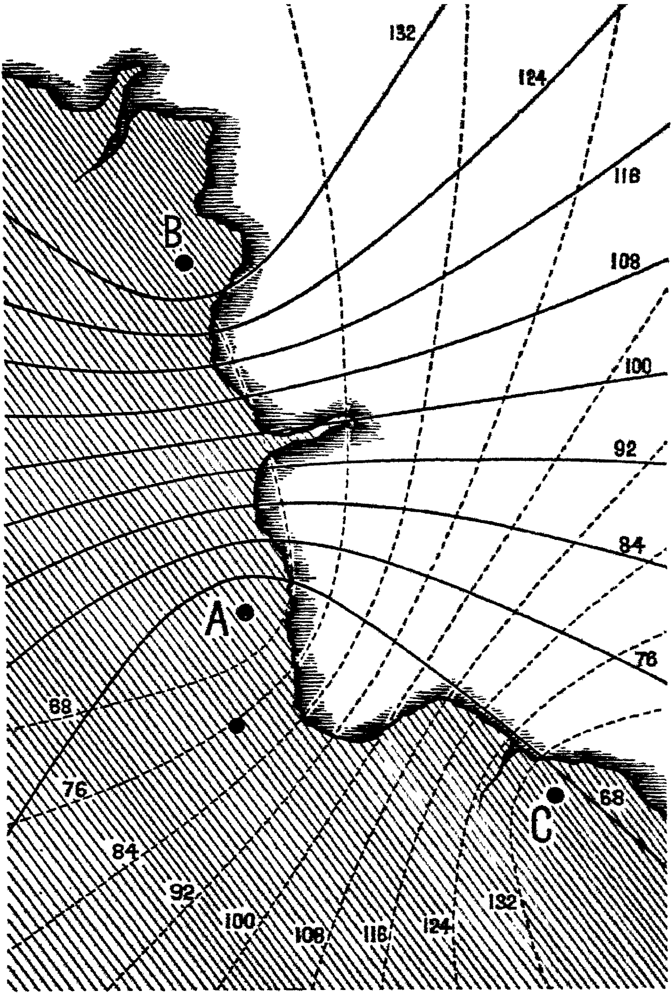
XI. ELECTRONIC NAVIGATION

WE HAVE NOWADAYS A RESPECTABLE CHOICE OF TRUE radar navigational aids, apart from those such as the QM and Console, which are not within the strict scope of pulse-radar navigation.

There is H2S in its many forms, Gee, G-H, Oboe, Babs, and Rebecca, and even that does not cover the entire field. H2S-type systems, as previously described, do not demand any co-operation from the ground, and are virtually 'television' devices. Babs and kindred systems take their name from the initials of 'beam approach beacon systems' of aircraft guidance while landing, and Rebecca systems again represent radar beacons which do not transmit continuously, but respond only to code inquiry.

The biggest field for the present of the true electronic navigational aids is held by Gee, G-H, and Oboe, and they all had their beginnings in the years when long-range radar navigational aids were vitally necessary to guide bombers over enemy targets, and to bring them safely back.

On the face of things Gee appears so similar to non-pulse methods that it merits a close inspection to avoid this confusion. Ever since radio direction-finding became practicable it has been used to provide ships and aircraft with a knowledge of their position relative to fixed points. By taking DF cross-bearings of at least two stations an intersection of lines can be used to fix position, just as if visual cross-plotting methods were used. DF-ing by radio (using the frame-aerial directional properties, or the Bellini-Tosi crossed loop) thus



A FEW LINES OF A GEE LATTICE

A is the master, *B* and *C* are the slaves. The base-line is 100 miles, and the time-delay in microseconds is shown in each isochrone. By taking a fix on each base and plotting, the navigator can pin-point his position.

supplanted solar and stellar observations because of its convenience, but not because of its greater accuracy. By astronomical methods a really good observer can determine the position of a ship to within a mile or two, and of an aircraft to within eight miles, if circumstances are favourable. Errors in Bellini-Tosi or Adcock radio DF-ing are just as great, but do not depend, of course, on climatic conditions or visibility to the same extent as do astronomical methods. But until the newer techniques of radio DF-ing came into being radar or electronic navigational aids brought an entirely new standard of accuracy. With one radar system accuracy to within a few *yards* can be given, and it has, for instance, been possible to bomb a small group of private houses used as a Gestapo HQ from radar beacons about a hundred miles away. This new degree of accuracy is such that the geodetic surveys of the past cannot provide maps of sufficient reliability, and for the first time in history our navigational methods are really ahead of our existing maps.

The essence of the new methods is this: if two radar transmitters send out truly synchronized pulses—that is to say, the pulses of energy leave the aerials at the same instant of time—then a receiver situated anywhere on the perpendicular bisector of the straight line joining the two transmitters will receive the two pulses simultaneously, because any point in this bisector is equidistant from both transmitters.

At any *other* point there will be a time difference in the receipt of the pulses, because the receiver will then be nearer one transmitter than the other, so, of course, the pulses from one transmitter will reach there earlier, by a very minute fraction of time. The fact that it *is* minute need not worry a radar receiver, for, as we have seen in the introductory chapters of this book, the CRT

and its associated circuits provide a very useful electronic stop-watch, capable of indicating millionths of a second.

Now with our two radar transmitters we could plot a very large number of positions where there are time differences, and sets of lines could be drawn, *joining all the points having the same time differences*, with respect to these two transmitters. Such networks of curved lines we call a grid, but it is worth noting that internationally we have agreed to call the lines themselves 'isochrones,' just as the lines joining all points on a weather map having the same barometric readings are called 'isobars.' Generally these isochrone lines are hyperbolæ, not straight, but curving outward on either side of the zero isochrone, and bunching close together, but never crossing, as they pass between the transmitter stations.

Time differences are displayed on a CRT linked to a receiver on the ship or in the aircraft; and if the observer notes, for example, that the pulses arrive from stations *A* and *B* 20-millionths of a second apart he would know that he must be situated *somewhere* on one of a pair of conjugate hyperbolæ, of which *A* and *B* are the foci. There is, in navigational practice, no need for him to make such a mathematical note. If he regards stations *A* and *B*, synchronized, as 'blue' stations, he merely looks at his Gee chart of curves and notes that he is somewhere on 'blue 20.'

Now he turns to another pair of stations—although let us note here for convenience that one may be simultaneously the second station of the first pair—*i.e.*, station *B*—and takes a reading from this second, or 'red,' group of stations. His map or Gee grid chart will have ruled on it intersecting 'families' of confocal curves, coloured blue and red respectively, and numbered at intervals just like the contour curves or isobars of a weather map.

A radar navigator working on Gee reception has thus to follow 'blue 20' curve with his pencil until he meets 'red 16,' when he can fix with great precision the position of his receiver at the intersection of the two isochrone curves, on both of which he is at that moment situated. In practice he takes his reading, notes the exact time on his stop-watch, and then does the 'final fiddling' afterwards, logging the exact time of the reading.

There is no co-operation, you will see, between the Gee network of transmitters and the receiver. Any number of receivers may work off the Gee station without fear of overloading. For civil aviation Gee offers a very practical advantage in that we know it works because it has been set up on a considerable scale all over Europe. You will find most Gee transmitters working on frequencies around 60 Mcs, but the possible Gee range is from 20 to 85 Mcs. At 15,000 feet a range of some 400 miles is quite usual with Gee equipment, and, of course, there can be no point in using wavelengths far removed from the customary 6 metres; there can be no overloading, any more than there is limit to the number of broadcast sets which can be tuned at any one time to a B.B.C. transmitter. The standard frequencies are sufficiently high to be immune from much static and similar interference, and Gee can be used in mountainous country with ease and accuracy. An important point is that the system is international and introduces no language difficulty. Limitation of range is a disadvantage, and the error at 300 miles is plus or minus ¼ per cent., and so the system cannot be used for blind approach. The standard equipment weighs about 70 pounds, which is not considerable.

This is the basic method of navigation which in its British form is known as Gee—a code word which seems destined to live; using longer wavelengths, the

system has been developed by American scientists, and is there known as Loran, an abbreviation of 'long-range navigation.' The Loran system has the advantage over Gee in that its pulses, on longer wavelengths, are propagated over wide stretches of the earth's surface by multiple reflection from the ionosphere, but it suffers from the disadvantage of all other reflected propagations in that path-lengths are not precisely determinate, and the errors of position-finding are in consequence usually somewhat greater. Loran enthusiasts claim that although its daytime ground waves cover about 500 to 700 miles, which is not much more than with Gee, the night-time sky waves extend coverage up to some 1400 miles. There is a difference in the time taken to get a fix on these systems. In Gee pulses from both pairs of stations appear on the CRT at the same time, and readings are taken simultaneously. In Loran only one set of readings can be taken at a time. The difference is about two minutes, as an expert Loran operator can seldom get a full fix in under three minutes, compared with the sixty seconds or less for Gee.

Within a year after the War American radar experts had seen much success in the installation of a Loran chain. Loran coverage stretches west across the Atlantic, North America, and the broad reaches of the Pacific. Loran transmitters have been installed in the Himalayas to guide traffic across the Hump. There is, of course, close co-operation between the pioneers of the two systems, and even during the war years as many as 800 aircraft of Bomber Command were fitted with dual sets which could handle both systems. Loran's chief feature, as its name implies, is that it is a long-range system, and with only four times as many transmitters as Gee its coverage is twenty times as great. It already covers more than a quarter of the earth's surface, and physicists who

are working to extend its range like to joke about the time when with a transmitter at each pole and four around the equator Loran will cover the world.

A reason for the great secrecy about Gee and similar systems during the War was the obvious fear that if the beacon transmitters were jammed by enemy signals the navigational aid might become useless. Of course, the enemy did attempt to jam, and arising from our counter-measures is some information which may later be of great use in civil aviation over territory where atmospherics and local bad reception conditions make Gee working difficult.

One of the most successful anti-jamming devices was the XF. Under this stratagem a new transmission on a frequency different from that being used comes up suddenly, synchronized with the preceding transmission. In wartime conditions this new frequency, known as the XF frequency, was usually switched on suddenly just before the first bombers were about to reach their target. While the enemy listening stations were discovering the XF and the jammers scrambling around to retune their transmitters to jam this new channel Allied navigators could get their fix, and so find their last short stage to the target.

Oboe, like Gee, is virtually a radar beacon. It does not 'see' things, nor depend on radar echoes, but the important difference between Gee and Oboe is this: with Gee there are slave and master beacon stations transmitting continuously, and all the adjustment, calculation, and work of obtaining a fix is done by the navigator. In Oboe all the control of the operation is done from the ground, and the installation in the aircraft is as simple as possible. The accuracy of Oboe too is of a higher order.

With Gee it is possible for a navigator to tell his pilot

how to get across some 300–400 miles of unknown country and find a large town, without any guidance other than the Gee master and slave transmisssion. With Oboe it is possible for the same journey to be made over entirely unknown country, and for the arrival spot to be pin-pointed with an accuracy of *yards*. The original plan was to develop Oboe with apparatus in the aircraft or ship as simple as possible, and at a later stage of development it was hoped that it might, in fact, be possible to dispatch the aircraft with no crew at all, the Oboe being automatic.

Oboe is a responsor system, like so many radar beacons; it does not depend on an echo from a distant aircraft, but pulse transmissions from the ground stations, on arrival at a distant outfit, trigger it off and cause a second pulse to be transmitted.

Oboe, which was born in Britain in 1941, consists basically of two ground radar stations, *A* and *B*, which both obtain responding pulses from the Oboe-controlled aircraft. A small transmitter in the aircraft is pipped-off on receipt of the ground pulses, many times a second. Ground station *A*, known as the 'cat' or tracking station, defines a narrow track at constant range from the transmitter by sending out signals in dot-and-dash form to the pilot. In early forms of Oboe the amplitude of these dots and dashes, which can be injected into an aircraft intercom system, tells the pilot how far he is from the correct track. In later versions rate-aiding principles have been applied, and the amplitude of the dots and dashes thus tells the pilot, not when he is on the track, but when his heading is correct—that is, when he is making accurately towards the desired target or airfield.

Ground station *B*, known as the 'releasing' (from the days when Oboe was devised as a wartime bomb-aiming

device) or 'mouse' transmitter, measures the ground speed of the aircraft as it approaches its home run along the track, and sends a signal to the navigator when he is immediately over it, if the need is to drop bombs, or when he is suitably approaching for a landing. On some wartime aircraft it was arranged that this Station *B* 'mouse' signal itself released the bombs, and, of course, there are several obvious peacetime applications of such a radar-controlled relay. To try the system as quickly as possible during the war years Oboe Mark I was produced using carrier frequencies in the 1½-metre band. It was planned that if this apparatus were successful centimetric Oboe could be used. First trials were made over the Bristol Channel on 1½ metres, and were very successful. Development of Oboe has been a joint American-British venture, for during the War a scheme was drawn up whereby all the Oboe receivers both for R.A.F. Bomber Command and U.S. IXth Air Force were made in Britain, and all the miniature centimetric transmitters and the special Oboe transmitting valves needed by the British and American forces were made in the United States. With this sort of apparatus jamming is very difficult, and it appears from numerous tests that the accuracy of the range measurement is of the order of yards, and is substantially independent of range.

As with Gee, the Oboe navigational systems are more accurate than the maps available for them. In present times, of course, this is not a serious problem, for the cartographers can set no frontier limits to their work in the international good. But in war it is a serious difficulty, for there is little point in building up a radar system which is very accurate, but rendered useless because the enemy maps available do not represent the necessary degree of accuracy!

A case in point arose in December 1942, when the

first trial bombing raid was made on the Ruhr by Mosquitoes flying at 28,000 feet on a wild winter's night. The aircraft were navigated to some point on the circular track about 50 miles from the target by Gee. Oboe control then took over, and the pilot was given signals to guide him along the curved track. Signals were given from the 'mouse' station to tell the bomb-aimer when he was approaching the target, and finally a signal was sent which accurately defined the release-point. So successful did the results seem that it was decided to hold calibration tests to ensure that the German air-maps available to us were accurate enough for Oboe calculations. In the first calibration raid on a small German-held aircraft centre in Belgium one bomb hit the building and another fell at the entrance, killing the sentry. Thus it was proved that the system was extremely accurate, and that the tying-up of the German and British maps had been done successfully. When you realize that the bombing in this case, as with all similar Oboe ventures, was done really by the ground operator, some hundreds of miles away from the target, or from the operator dropping the bombs, the system appears all the more remarkable.

How do the 'cat' and 'mouse' stations get their ranges by radar? Remember that the aircraft carries only a mobile transmitter-receiver, and no measuring device. The ground stations send out their pulses, these trigger off the airborne set, and new pulses come back home to the 'cat' and 'mouse' receivers. The total time for each of these transmissions is made up of a number of complicated parts—for instance, there is the time of outward travel, time delay in triggering off the mobile equipment, and time of the return to the ground station. The time of the second journey must be known accurately, for this gives the range of the aircraft from the fixed station.

Each ground station has the information that the aircraft is at a known distance away, so the position lines are circles with the ground stations at their centres. By comparing notes the fixed stations can determine the position of the aircraft, and can then send the 'mouse' signal to the navigator, pilot, or bomb-aimer. Of course, the whole system could be reversed. The mobile station could initiate pulses and measure the time of the 'interrogated' pulses from fixed ground responder stations. Whichever way round the system is worked, a transmitter has to be carried by the mobile station. One operational advantage of Oboe in normal circumstances is that the task of getting an accurate fix is done in the relative calm of the ground stations, and the calculation does not have to be carried out at the airborne or ship-borne end.

Gee cannot be overloaded by a large number of receivers being tuned at the same time to the ground stations. Oboe, however, is directed to one group of mobile transmitter-receivers. A third system may be needed to give very precise marking of small targets, or so that a number of tactical targets can be covered simultaneously by a considerable number of aircraft. The G-H system offers possibilities, and it is derived from the Gee system. The 'H' principle consists of measuring with great precision the range of an aircraft or ship from two fixed beacons. In contrast with Oboe, where ranges are measured on the ground, in G-H they are measured at the mobile end. The number of aircraft which can use the system is limited only by the power-handling capacity of the beacons. A transmitter at the mobile end sends out a pulse, and this is received by each of the ground beacons and returned to the aircraft *on a different frequency*. The time taken for this process gives a precise measurement of the two ranges, the

delays in the beacons having been previously and accurately ascertained.

When the range of the aircraft from the two fixed ground beacons has been determined the 'fix' has been obtained. In addition to knowing its position, however, an aircraft requires to know its ground speed, both in magnitude and direction, before bombs can be so released blindly that they will hit the target. Similar information is equally necessary for safe landings. Direction of flight is obtained through the aircraft flying along that circle of constant range from one of the beacons which passes through the target or landing-field. Ground speed is determined by measuring the rate of change from the other beacon. Accuracy of the system depends on one curious factor, as a little careful thought will show: it depends on the position of the target or landing-field *relative to the two beacon stations*. This accuracy decreases as the angle of intersection of the two constant-range circles through the target decreases. The combination of Gee and H in G-H is a happy one, for in many operational circumstances Gee can be used for the general navigation, and then the system can switch over so that the H part can be used for the final run-in.

Depending, as these systems do, on the precise measurement of the time differences in the arrival of pulses, either direct or triggered, Gee and the kindred systems have set a new standard of accuracy in radio navigation, but there are practical difficulties in using these systems for civil flying. Military aircraft carry a navigator who can take Gee readings and secure fixes. Civil aircraft always carry as small a crew as possible, for obvious reasons, and the desire has been strongly expressed that all navigational aid should be presented direct to the pilot.

XII. TRAVEL BY BEACON

THERE ARE RIVAL SCHOOLS OF THOUGHT IN RADAR. Some people like to *see* things; others are content to let things *guide* them by beacons and other impersonal aids. It is certainly more fascinating, from the layman's point of view, to 'see' the ground by H2S than it is to visualize an aircraft guided by the more complex beacon systems, with their jumble of unmusical pulses; but then the layman does not have to fly aircraft, or (directly, at least) pay for the equipment used.

Although beacons do not show the pictorial results of, say, H2S, they are an important part of radar because of their simplicity. Oboe and Gee, as we have seen, are really beacon systems of a sort, but here we are going to examine other radar beacons and navigational aids, notably Babs, SCS-51, an American-designed beam-approach system now produced in Britain, and Rebecca.

One of the fundamental principles of many radar beacons is that of the 'transponder.' Once it was established that pulses from a radar transmitter could be received and used to trigger automatically another pulse transmitter with uniformly negligible time delay (not necessarily repeating the original pulse form, nor re-transmitting on the same frequency) it became clear that such a 'transponder' could be set up at any convenient place and would act as a radar beacon. An operational advantage of such a beacon is that it maintains 'wireless silence'—in effect, speaking only when being spoken to. Moreover, it is capable of being made to respond only to certain coded sequences of pulses on a given frequency, and to give accurate information of

the distance between the beacon and the interrogator. Such an estimate of distance is obtained, usually, in the well-known Type A display manner, with the beacon and interrogator pulses showing along a straight-line trace, the time interval between them being easily interpreted into distance.

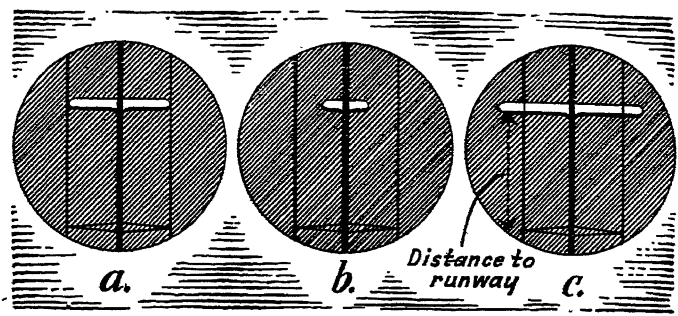
Much of this beacon development arose out of IFF. Ships and other vehicles of war carried small transmitter-receivers which, on being triggered off by detecting ground stations, could automatically emit coded pulses. These pulses show up at the ground station, usually in addition to the echo received back; if the coding is correct, then obvious indication is given that the mobile outfit is carried by a 'friendly.'

The network of beacons which came to be relied upon in war may become an important adjunct to navigation to-day, at sea and in the air. Earliest beacon signals were presented to the navigator of the questioning craft as fluctuating blips on his Type-A-displayed range-scale, together with whatever indication of azimuth (bearing) the apparatus might be capable of displaying. But with the introduction of PPI technique the beacons show up as 'winking' spots or arcs of light in their positions relative to the interrogator, on the scale of the map-like PPI picture.

Comparison can be made between these transponder beacons, which blip only when blipped at, and the reflecting signs on our main roads, which glisten and warn motorists only when the car headlamps illuminate their midget reflectors.

Beaconry in radar offers a wide scope, for we can have fixed marker beacons or we can arrange to drop beacons on parachute harness or fit them to buoys at sea. Safety aids use radar beacons extensively, and a wartime air-sea-rescue system which has now grown up to peace-

time proportions uses a rather ingenious radar beacon. This incorporates a squegging oscillator which can be coded in dot-and-dash form, to act as a beacon to summon and guide help to air-liner passengers and crews in distress at sea. When the survivors from an air accident over sea have clambered into their dinghies a small box can be set up to send for many hours an



WHAT THE NAVIGATOR SEES IN A BABS DISPLAY

(*a*) Aircraft dead on line.
(*b*) Runway on left *or* aircraft too much to starboard.
(*c*) Runway on right *or* aircraft too much to port.

Note. The drawing is merely illustrative, and is not to be considered accurate in detail. The blip in the centre picture would in practice be thicker than the one on the right.

intermittent pulsed signal which will show like a beacon on the radar display of searching craft.

Among the numerous track guides and instrument approach systems predominant is Babs, the beam-approach beacon system. It enables aircraft to be brought to the boundary of an airfield with precision, and with most types comes into operation first when the navigator is about 20 miles away from the field. The Babs equipment on the aerodrome consists of a small transponder (transmitter and receiver), situated at the

end of the runway, and accurately aligned so that the major beam of transmission is correct for landing conditions. The fixed installation is erected for the main runway, and the other runways are usually served by mobile equipment.

The airborne part of the Babs equipment, the interrogator, sends out signals which are received by the transponder at the end of the runway and retransmitted in a very sharply defined beam, the central axis of which is switched rapidly first slightly to the left for a short interval, then slightly to the right for a longer interval.

When the homecoming aircraft is 'in' the beam—that is, exactly in line with the runway—signals from the Babs beacon will appear level on the CRT screen, and if pips are being injected into the intercom, then a continuous, steady howl will be heard.

If the pilot is approaching too far to the right of the runway a series of dashes will be heard in the intercom, and broad echoes will show up on the CRT.

As he changes course to the left the broad echoes become shorter, and small, narrow responses or 'dot' signals will appear. Any deviation to one side or the other immediately produces corresponding changes in the echo blips. The position of the blips on the CRT is a continuous indication of the distance of the aircraft from the end of the runway, and thus the navigator or observer with Babs is able to pass to the pilot a steady flow of information which should bring the aircraft over the edge of the airfield, at a comfortable height and heading straight for the runway—and the pilot knows that he can rely on it. The half-degree-wide beam of Babs should bring the aircraft in not more than twenty yards either side of the centre line of the approach end of a runway 2000 yards long. Lights will then enable

the pilot to complete his landing visually in all but the worst weather conditions.

Babs has the advantage that it was used throughout the War with confidence, and many other branches of beaconry have developed from Babs technique; it is therefore a well-tried radar equipment and popular with crews who have been taught the drill on this type of radar aid. It also has the advantage that it is international, presents no language difficulties, and is reliable owing to its simplicity. Operational disadvantages put forward by some navigators are that the CRT is rather bulky if the range is to be effective, and the presentation is not so 'pictorial' as that given by, say, a PPI display.

British and American scientists have made valuable contributions to the technique and practice of beaconry, and an interesting American development is the blind-approach system known as SCS-51, which works usually around 100 Mcs.

In most commercial forms of this equipment there is a 'localizer,' a 'glide-path,' and three marker beacons. Each of these beacons transmits on a different frequency (or, in a certain variation of the system, on the same frequency, but with different PRF's), and each is given a different CRT display in the cockpit. In certain equipment where there is no CRT display milliammeter needles show what is happening. With milliammeter display the instruments used are of the centre-zero type, and are placed in a balancing network so that all the pilot has to do is set a course on which the milliammeter needle shows a centre reading. Deviation from the true course—that is, head-on to the appropriate radar beacon—will be shown by corresponding milliammeter needle swing. Each beacon is sharply beamed by directional aerial arrays.

Of the various ground beacons in SCS-51 the 'local-

izer' assists the aircraft to get in line with the runway, from a distant point, and guides it in to the centre of the runway. There is no continuous range indication, but the three marker beacons are placed to indicate the start of the descent, the approach end of usable runway —and one also acts as a central checking-point. With the glide-path ground transmitter and associated equipment this is a comparatively costly outfit to work, but in practice the aircraft can be localized to within 0·75°, and the glide-path checked to within 0·3° above or below. There are no language difficulties with SCS-51, for the pilot has to get no instructions from the ground.

A beacon system which has many characteristics similar to Babs is Rebecca, with its variant, Rebecca-Eureka. Whereas Babs is a generic term covering a number of radar systems of beam approach on airfields, beacons of the Rebecca type respond only to coded interrogation. In the Rebecca-Eureka system small beacon transmitters (the 'Eureka' part of the equipment) can be dropped by parachute: they remain quiescent until an aircraft carrying the Rebecca interrogator approaches to within, say, 20 miles. Then the Eureka beacon begins transmitting pulses which show up on the CRT carried in the navigator's cockpit. Under war conditions beacons which respond only to certain codes, or to certain types of interrogator, have their obvious uses, as security is improved. Such a radar system does not broadcast continuously, but is interested only in some minute fractions of time—for instance, 15 microseconds within each three-millisecond period of time. But when the air is crowded with civilian traffic the same difficulties may be experienced, and the advantage of coded beacons is obvious.

Beacons can provide an indication of bearing with a remarkable accuracy, but for air-travel we must know

more than bearing; we must have some radar device to indicate height.

The altimeter is an essential flying instrument, and for many years the only indication of height was the reading of an aneroid barometer which had been set before take-off to the height above sea-level of the airfield from which the flight started. Even if the weather conditions did not change during the flight the best that could be expected was that while over water or land at sea-level the aneroid would register 'true clearance.' The same reading would be obtained in level flight if, a few minutes later, the aircraft flew over mountain-peaks 10,000 feet high, with disastrous results if the flight altitude were only 9000 feet. This is not a fanciful possibility, for only too often have aircraft flown into mountain-sides in weather so 'thick' that disaster was upon them before the air-crew could take evasive action. What was needed, clearly, was an instrument to show 'terrain clearance,' which is the true distance from the aircraft to the nearest part of the earth's surface, with some sort of warning indicator, so that if this aircraft-to-earth clearance became dangerously small the pilot could gain height and avoid danger. This the aneroid-type altitude indicators could never do, for weather and various barometric changes might result in a long-distance aircraft returning to base with its altimeter in error by several hundreds of feet.

Normal pulse-and-echo radar systems have a disadvantage in that at very close distances from the ground the time interval between pulse and its echo becomes extremely small, so there is a minimum height at which such equipment can be used. Early radio altimeters were, in effect, a normal pulse-sender and echo-detector, and measured heights with a considerable degree of accuracy. But they fell into disuse because at any

distance from the ground less than about 400 feet they proved unreliable. CRT display is also apt to become a nuisance for altimeter work. The picture on the CRT is helpful to the navigator for range and bearing, for PPI pictures, and for many other purposes. But in the field of altimeters all he wants to know is, "What is the altitude?" The answer is perhaps best shown on an instrument dial rather than with the electric pencil-point of the CRT. Moreover, the associate apparatus necessary for CRT display takes up space in the cockpit.

In present popular electrical altimeter systems the transmission is not of pulses, but of continuous waves. They are emitted with rhythmic variations in frequency from the underside of the aircraft. The reflected wave from the earth's surface is received back and 'compared' electrically with the waves then being sent out. The longer the time interval between the emission of the original wave and its reflection back to the aircraft —that is, the higher the aircraft is flying—the more will its frequency differ from that of the wave being emitted at the instant it is echoed back. Thus the altimeter receiver is simultaneously fed with two streams of waves, one from the transmitter and one reflected back from the ground. These differ by an amount proportional to the altitude of the aircraft. The receiver measures this frequency difference and shows the result on a dial as terrain clearance. Terrain clearance may also involve the measurement of clearance obliquely ahead, as in the approach to or flying through steeply mountainous country.

For simplicity radio altimeters of this type do not show minute changes in altitude, but record only in steps of six feet (on the 0–400 feet scale) or 60 feet (on the 400–4000 feet scale). Apparatus of this type has a reasonable error. In the 50–400 feet sector, for instance,

there is a plus-or-minus error of 6 per cent. With some types of altimeter there is a limit indicator to relieve the pilot of the necessity for watching the altitude scale all the time. It consists of a small panel on which are mounted three coloured bulbs, green, amber, and red. These come into circuit as the altitude of the aircraft varies in relation to that indicated by the position of the limit switch, which, of course, can be controlled at the pilot or navigator's wish according to the type of terrain over which he is flying. In the British arrangement the green signal lamp indicates that the aircraft is flying at approximately the pre-set altitude. The red bulb indicates flight below and amber above that altitude. American practice reverses the green and amber. It is obviously not impossible to link such a device with an automatic pilot, enabling the aircraft to be flown hands-off at a predetermined height within the range limit of the altimeter.

It should be appreciated, therefore, that radio altimeters of this type do not depend on pulse and echo, but on *frequency difference*. A continuous-wave signal is continuously, rhythmically changed slightly in frequency, and this is fed into a receiver as well as into the frequency-modulation side of the transmitter. The echo is received back from the ground, and its frequency difference is measured from that of the signal which is at that same instant being transmitted. It is this frequency difference which is proportional to height above ground.

XIII. CONCLUSION

THAT THE STORY OF HOW RADAR WORKS CAN BE TOLD in a book published in the English language is in itself a tribute to radar's operational success in war. In a world of international emotion and political misuse of power it is impossible to separate radar progress from its war potentiality, and although the applications of radar and similar electronic navigational aids and other devices for the uses of peace are now boundless, it can never be forgotten that radar did indeed protect these islands from enemy invasion.

Although pulsed light and the new techniques of supersonics may be used in wars yet to come to guide projectiles of attack, radar remains the first and still the most important system of direction-finding, of navigational aid, and of direction of aircraft, ships, vehicles.

The story which I have attempted to tell in this present book must be hampered by the nearness of the recounting to the momentous historical events of the present time, so that all nations are fearful of disclosing their radar discoveries. But it must be put on record in this concluding note that these radar devices which have transformed every major aspect of war were born in Britain of a timely combination of scientific imagination, technical resource, operational appreciation, and organizing genius. The scientific imagination was exercised in taking the step from old knowledge, available to every one, of many isolated facts and methods in radio research, to a coherent new system fitted to military needs and capable of use by military personnel. The old knowledge—much of it very old—was international in

its origin, much of it British, some of it American, the crucial part of it a British experimental method.

The technical resource was exercised in producing, under severe difficulties imposed by the wartime need for stringent secrecy, pulse transmitters of unprecedented power, receivers of unparalleled sensitivity, aerials of unique design, ancillary equipment of novel character, all doing somewhat better than before something previously done after a fashion, some doing things never done before.

Radar was a direct but not an inevitable fruit of pure research. On probably no other subject can we say with so much truth, "If it had not been for the War . . ." Britain had for many years been a prominent leader in pure research on the travel of radio waves, on the things which make long-distance radio communication possible, and on the things which still cause it to be imperfect. The Department of Scientific and Industrial Research had followed the very enlightened policy of accepting the advice of its Radio Research Board that the best contribution which it could make to better radio communication was the long-term and fundamental investigation of the basic processes, rather than the short-term search for individual remedies to individual problems. Whether this pure research should be fostered and supported by industry, by scientists themselves, or by the State has now become not only a political but an international matter.

In radar there can be no boundaries, and in the long run, as with the harnessing of atomic power, no secrets. From the pioneering days of Appleton and Watson-Watt with experiments in the ionosphere and in pure research on the reflections of radio waves from solid bodies we have progressed to a multitude of navigational and directional radar devices. This multitude combines to

make a weapon too great for any one man or any one nation to hold. Although the people and even the scientists are reluctant to realize what has happened, the baby of radar, born in the nineteen-thirties in Slough, has risen from that despond to become a giant. In his youth he saw valiant war service. It is now desperately essential that he remains a peaceful civilian.

APPENDIX

NOTES ON THE PLATES

Plate I (*frontispiece*). The modern aircraft carries a wealth of radio and radar equipment. This composite picture shows sixteen major electronic devices to aid pilot and navigator. (1) H2S, with an impression of a typical radar ground map as seen on the screen. (2) Wireless telegraphy link. (3) Radar Gee system of long-range navigation. (4) Radio track guides, using Standard Beam Approach to guide aircraft to known airports. (5) Medium-frequency beacons, for use with a loop aerial inside the aircraft. (6) Main beam-approach system, injecting dots or dashes into the intercommunication system to inform a pilot when he is to port or starboard of correct course. (7), (8), and (11) High-frequency direction-finding aerials and very-high-frequency transmitter for use by Flying Control and for airfield signals. (9) and (10) Inner and outer marker radio beacons. (12) Very-high-frequency communication with other aircraft. (13) Medium-frequency direction-finding stations. (14) Identification of Friend or Foe radar system used in military aircraft. (15) Attack-warning radar system used in military aircraft to give warning of aerial attack. (16) 'Mountain Goat' radio beacon to warn navigators of high ground, cliffs, and mountain-peaks.

Plate II (*p.* 112). *Type A Range Display.* The horizontal bright line, known as the 'trace,' is constant. The vertical deflections, showing as spikes of light, indicate radar reflections from various objects. The rule above the trace is graduated in miles. The 'echoes' seen from the base (0) up to 20 miles are from fixed near-by objects such as hills, masts, and towers. They are permanent echoes, known as PE's. A live response from an aircraft some 52 miles away can clearly be seen.

Plate III (*p.* 113). The H2S system paints on the radar screen a rough map of the ground beneath an aircraft. The actual photograph (*left*) of a radar screen shows how the picture appears to be traced out. Coast and sea areas are clearly marked. The true map is shown on the right, and comparison can thus be made between this and the radar image of the characteristic English coastline of the Wash.

Plate IV (*p.* 128). Marine radar can be used for locating coastlines, buoys, other ships, and even aircraft. The bright lobe above this ship represents the radar rotating beam. The small circle (*inset*) indicates approximately what is seen on the ship's radar screen. The big 'blip' represents the pulse caused by the ship's radar transmission signals. The small echo *A* is the response from aircraft *A*, which is not fully in the beam. Aircraft *B* is right in the beam, and causes the deeper 'blip.' The ship's beam can similarly be swung or rotated to scan the coastline.

Plate V (*p.* 129). *The Operation of Gee Radar.* (*Left to right, above.*) Two Gee transmitters are equivalent to two stones dropped simultaneously into water. The white line illustrates ripples at a point equidistant from the centres of splashes. At points *not* equidistant from two wave sources the difference in arrival-time of waves or 'ripples' indicates the position on a series of hyperbolic lines. In practice Gee can use three transmitters, *A* being related both to *B* and *C*. On the Gee tube in the aircraft transmissions from these three stations are seen as spikes of light on the trace.

(*Left to right, below.*) The Gee receiver time-base is adjusted to align the 'blips' in relation to the strobe. These readings are then translated into figures by switching on the timing 'Cal' (calibrator) pips, which the navigator can match with the received signals. These figures relate not to mileage or bearings direct, but to numbered lines on the Gee charts. In the final picture this position is seen being ascertained and marked with an *X*.

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